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SOME NEW RELATIONS BEARING ON CONCRETE MIXTURES

BY THE DIVISION OF MANAGEMENT, UNITED STATES BUREAU OF PUBLIC ROADS

Reported by William A. Blanchette, Highway Engineer, Division of Management, United States Bureau of Public Roads

IN INVESTIGATIONS recently conducted at East Point, Ga., the Division of Management of the United States Bureau of Public Roads has studied the effects of variation in the proportions of the solid ingredients of concrete and its water content upon the quality of the resulting mixture as measured by its density and strength. The tests have developed indications of certain relations not heretofore established which it is believed constitute an addition of fundamental importance to the knowledge of the character of concrete mixtures.

Perhaps the most widely accepted generalization concerning the strength of concrete is the water-cement-ratio theory which suggests that the most important factors in determining strength are the relative amounts of water and cement.

To this concept the work of Talbot and Richart has added, with respect to mortars, definite knowledge of the relations existing between the water content and the voids in the cement-sand mixture and the bearing of these relations upon the strength of the mortar. They showed definitely that for any given combination of various amounts and kinds of cement and sand addition of a certain amount of water will produce a mortar of maximum density, and they called this amount the "basic water content." With all other amounts of water, either greater or less than the basic amount, a lesser density was obtained in the resulting mortar.

It was found convenient to express the quantity of water added in terms of the basic quantity as a "relative water content" by means of an index figure. Thus, a mixture containing an amount of water one tenth greater than the determined basic quantity was said to have a relative water content of 1.1.

In the investigations conducted by the Division of Management the method of determining the amount of water required to give maximum density to each particular combination of materials was similar to that of Talbot and Richart except that in this work concrete mixtures were used instead of mortar mixtures.

NEW RELATIONS DEVELOPED

The principal new relations developed are as follows:

1. For a particular combination of sand and cement a relation exists between the amount of coarse aggregate in the mixture and (1) the amounts of water required as the basic and various relative water contents and (2) the corresponding total voids in the mixture. As the coarse aggregate content is uniformly increased, the amount of water required for the basic and each relative water content and the total voids in the concrete corresponding to each, are uniformly decreased.

2. Likewise, for a particular coarse aggregate content, a relation exists between the ratio of the amounts of sand and cement in the mixture and (1) the amounts of water required as the basic and various relative water contents, and (2) the corresponding total voids in the mixture. As the sand-cement ratio is uniformly increased, a uniform change occurs in the amount of water required for the basic and each relative water content and the total voids in the concrete corresponding to each. In these tests, increase in the ratio of sand to cement resulted in an increase in both the amounts of water required for each relative water content and the corresponding total voids in the concrete.

3. For each relative water content, using the same kinds of materials, the slump of every concrete mixture will be the same regardless of the proportions of cement and aggregate used in it.

MECHANICAL METHOD DEVISED FOR MOLDING TEST SPECIMENS

The studies were to involve the molding of concrete specimens with various water contents for density determinations. The densities determined were to be used in drawing concrete-voids curves from which actual water requirements for each particular mixture were to be determined. Specimens for strength tests were also to be made containing the specific amounts of water as indicated by these curves. It was regarded as important that a method be used for consolidating both the density and strength specimens that would be consistent and uniform in its operation in order that the densities in the strength specimens should closely and uniformly approximate the densities of such mixtures as indicated by the concrete-voids curves. It was also desired that the method should be capable of reproducing in the density and strength specimens, a density corresponding closely with the density of concrete produced in pavements by the customary methods of mixing, placing, and finishing.

A mechanical compacting machine was devised and constructed for this purpose. The machine is driven by an electric motor and consists of a rectangular steel table, the drops or impacts of which are actuated by a series of gears and a cam, causing the table to rise and fall freely upon two 3-inch steel cylinders. These cylinders are bored to receive two 1-inch steel pistons which guide the motion of the table. The distance of fall and the rate at which impacts are delivered to the table can be varied, allowing the machine to be operated so as to produce a density in the specimen that tends to duplicate the density of the same concrete mixture as placed in a particular work by a particular method of manipulation.

Figure 1 is a detailed drawing of this machine and illustrations of it are shown in figure 2.

Considerable preliminary work was done to determine the extent to which the machine accomplished the purposes for which it was constructed. Density specimens were molded on the machine by different methods of operation. The concrete-voids curves resulting from these determinations indicated that the density of a concrete mixture could be changed by changing the operation of the machine, and that the machine could be operated in such a manner as to duplicate the density of the same concrete as placed in the work.

Comparisons were made of concrete-voids curves resulting from tests of specimens compacted by the mechanical method and by the standard method of hand

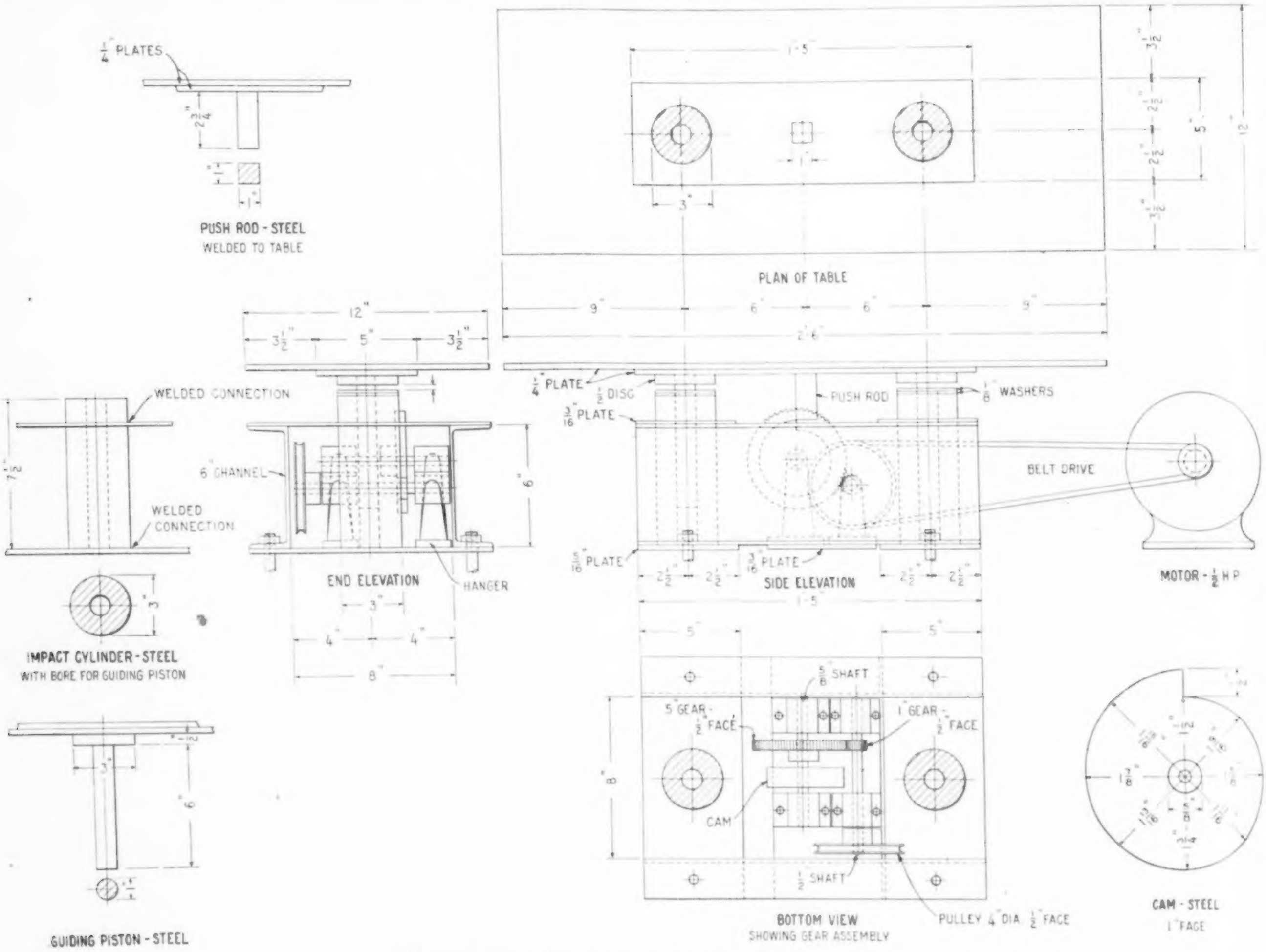


FIGURE 1.—MECHANICAL COMPACTION TABLE.

rodding. The results indicated that the mechanical method produced curves that were as regular and consistent as those produced by the standard method. Tests were made by different operators using both methods to determine how closely concrete-voids curves could be duplicated by different operators with each method. The machine method was found to be satisfactory in this respect.

The two methods were compared from the standpoint of uniformity of distribution of the ingredients in the molded specimens. This was done by splitting cylinders molded by each method into parts and analyzing each part to determine the amount of each ingredient contained in it. The results of this comparison showed that from the standpoint of uniformity of distribution of the ingredients, the machine, as it was operated, gave satisfactory results.

The two methods were next compared on the basis of strength results for cylinders and beams molded by each method. Comparison was made of the spread in strengths and the average deviation from the arithmetic mean for each individual set and for all sets made by each method. These comparisons showed that the mechanical method of molding strength specimens was as satisfactory as the standard method of hand rodding from the standpoint of uniformity of results.

OPERATION OF MACHINE DETERMINED BY EXPERIMENT

The method of operation of the compacting machine in making density and strength specimens was determined in the following manner: A hemispherical container of one half cubic foot capacity and a depth equal to the pavement thickness was placed on the subgrade in the rear of the mixer on a paving project. After the concrete had been deposited on the subgrade, spread, and had received the final finishing operation, the container full of concrete was removed and the concrete analyzed to determine the amount of each ingredient in it, and also the water and air voids and density of the concrete. Several of these determinations were made over a period of several days and the average value for density and water and air voids was determined. Identical mixtures were prepared in the laboratory from the same materials and specimens were molded on the machine using different heights of drop and numbers of drops. It was found that 340 drops of 1/64 inch in a period of 1 minute produced a density equal to that of concrete in the pavement. This operation of the machine was adopted for the subsequent tests. No appreciable segregation of ingredients was observed in the specimens. For proportions other than those used it might be necessary to vary the

operation of the machine somewhat. It is believed, however, that the operation as determined is sufficiently accurate and tended to represent the manipulation of the concrete as placed in the pavement.

MIXTURES USED IN TESTS DESCRIBED

In this investigation two groups of tests were conducted. In the first group the same brand of cement and the same kind of fine and coarse aggregate were used in all mixtures. The proportions of all ingredients were varied and the resulting strengths determined. In the second group three series of tests comprising combinations of different kinds of materials were made in which two brands of cement, one kind of fine aggregate and three kinds of coarse aggregate, were used. The ratio of fine aggregate to cement and the relative water content were constant for all three series. In each series the amount of coarse aggregate was varied from zero to the maximum.

Basis of proportioning.—Proportioning was done by absolute volumes. The symbols used are as follows:

a = Absolute volume of fine aggregate in a unit volume of freshly placed concrete.

b = Absolute volume of coarse aggregate in a unit volume of freshly placed concrete.

c = Absolute volume of cement in a unit volume of freshly placed concrete.

$b_s = \frac{b}{a+b+c}$ = Ratio of the absolute volume of coarse aggregate to the sum of the absolute volumes of fine aggregate, coarse aggregate, and cement in a unit volume of freshly placed concrete.

d = Density or solidity ratio of the freshly placed concrete.

V_c = Voids (air and water) in a unit volume of freshly placed concrete, equals $1-d$.

W_c = Volume of water per unit volume of freshly placed concrete.

$\frac{c}{V_c+c}$ = Cement-space ratio.

w = Relative water content.

$\frac{W_c}{c}$ = Water-cement ratio.

Water content.—The water contents used are expressed in terms of the basic water content, that amount of water which gives maximum density to the particular mixture, as determined from the concrete-voids curve for that mixture. A concrete-voids curve was drawn for every mixture used.

Physical characteristics of materials.—The physical characteristics of the aggregates and cement are shown in table 1. All aggregates were dried to constant weight before they were used.

Specific gravity determinations.—The specific gravities of cements and aggregates were determined in the following manner:

$$\text{Specific gravity} = \frac{W_a}{W_a - W_w}$$ in which W_a represents weight in air, and W_w represents weight when immersed in water. Cement was weighed in air in its natural state. Aggregates were weighed in air in a bone-dry state. Materials were weighed in water after a period of immersion approximating the time the cement and aggregate are in contact with water during the mixing and molding of concrete specimens before the specimens are weighed for the density determination.

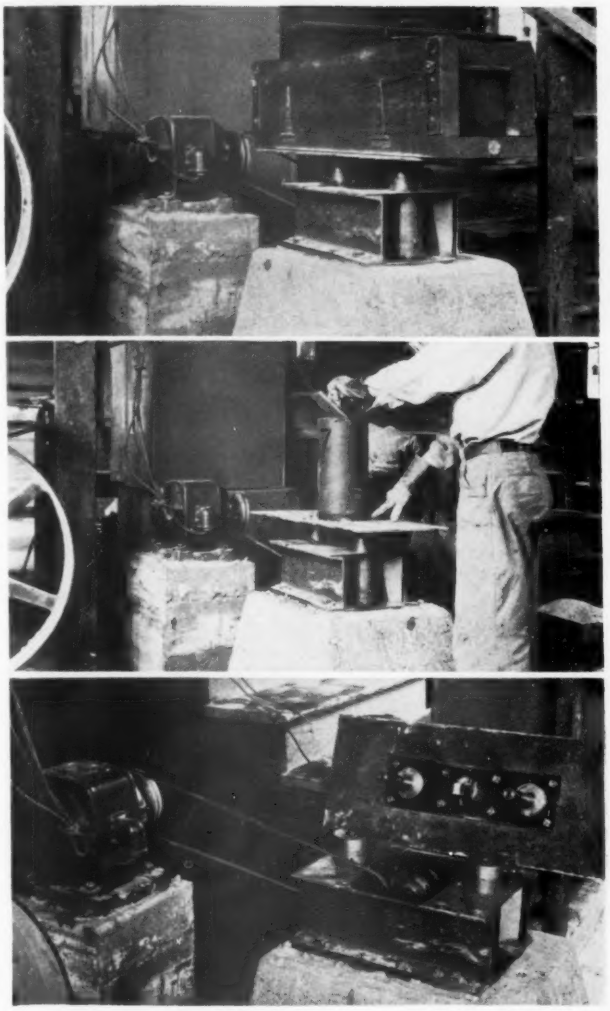


FIGURE 2.—MECHANICAL COMPACTING MACHINE BEING USED TO MOLD BEAM AND CYLINDER SPECIMENS. LOWER PICTURE SHOWS TABLE OF MACHINE RAISED TO EXPOSE CAM AND DRIVING MECHANISM.

TABLE 1.—*Physical characteristics of materials*

Material	Specific gravity	Percentage of absorption	Mechanical analysis, percentage retained on—									Fineness modulus
			1½ in.	¾ in.	⅜ in.	No. 4	No. 8	No. 14	No. 28	No. 48	No. 100	
Fine aggregate, sand, no. 1[1]	2.64	0.00	----	----	----	----	0.2	3.0	25.8	75.0	95.8	2.00
Coarse aggregate, gravel, no. 2	2.62	.50	0.0	38.2	92.5	98.6	100.0	----	----	----	----	7.29
Coarse aggregate, crushed limestone, no. 3	2.78	.39	36.0	80.0	94.0	99.7	100.0	----	----	----	----	8.10
Cement, no. 1	3.27	----	----	----	----	----	----	----	----	----	----	----
Cement, no. 2	3.24	----	----	----	----	----	----	----	----	----	----	----

[1] Similar designations by name and number represent similar materials throughout these tests.

TESTING PROCEDURE

Mixing concrete.—All concrete was mixed by hand on a steel mixing plate. The same operator mixed every batch throughout these tests.

Molding specimens for the density determinations by mechanical means.—A new batch of concrete was mixed for each density determination. The absolute volume of each batch was slightly in excess of the volume of a heavy steel 6- by 12-inch cylinder mold. The entire mold was filled with concrete, then placed on the table of the mechanical compacting machine and subjected to the compacting procedure adopted as standard for these tests. The mold was kept full of concrete during this operation. The concrete was then struck off even with the top of the mold and the density, water voids, and air voids of the concrete determined. Each point on the concrete-voids curves represents one density determination.

Molding strength-test specimens by mechanical means.—A separate batch of concrete was mixed for every 6- by 12-inch cylinder made. Paraffined cardboard cylinder molds were filled completely with concrete and placed on the table of the compacting machine. The machine was then operated to give the standard number of drops, the mold being kept full of concrete to overflowing during this tamping. The concrete was then struck off even with the top of the mold and its density determined. Two separate batches of concrete, one for each of two layers, were mixed for every 6- by 8- by 30-inch beam made. Beams were molded by filling the wooden mold completely full of concrete, using a separate batch for each of two layers. The mold was then placed on the table of the machine and compacted, keeping the mold filled to overflowing during the tamping. The concrete was then struck off even with the top of the mold and the density determination made.

Determining density and voids of concrete.—The outside of the mold containing the specimen was wiped clean and dry, and the weight of the concrete contained in the mold determined. The volume of the batch was determined by the formula:

$$\text{Volume of batch} = \frac{\text{Weight of concrete in original batch} \times \text{Volume of mold}}{\text{Weight of concrete in mold}} \quad \text{(1)}$$

The density of the concrete d in the original batch was determined by the formula:

$$\text{Density of concrete} = \frac{\text{Solid volume of cement and aggregates}}{\text{Volume of batch}} \quad \text{(2)}$$

The total voids in the concrete V_c equals $1-d$ equals W_c plus air voids. W_c, the volume of water per unit volume of freshly placed concrete, was determined by the formula:

$$W_c = \frac{\dfrac{\text{Weight of water added to batch}}{\text{Weight of water per cubic foot}} - \text{Volume of water absorbed by aggregates}}{\text{Volume of batch}} \quad \text{(3)}$$

Air voids equal V_c minus W_c.

Curing and testing.—All strength specimens remained in air for the first 24 hours. They were then placed in the moist room until removed for testing at the age of 28 days. Every strength specimen made was tested and the strength of every break is included in the analyses of results obtained.

FIRST GROUP OF TESTS DESCRIBED

These tests were made in an effort to determine the effect on the strength of concrete of the following: (1) Ratio of fine aggregate to cement; (2) amount of coarse aggregate; (3) amount of water.

Nine different mixtures of cement, fine aggregate, and coarse aggregate were used. All of these mixtures are considered to be within the practical limits of mixtures used in concrete pavement construction.

A concrete-voids curve was drawn for each of the nine mixtures to determine the amount of water required to give maximum density to the concrete (basic water content) and to find the amounts of water to be used in the strength specimens in terms of this basic water content.

After determining the basic water content for each mixture from the concrete-voids curves, six 6- by 12-inch cylinders, two 6- by 8- by 30-inch beams and one slump test were made with each of the nine mixtures for each of the following water contents: 1.00 relative, which is basic water content, 1.10 relative, and 1.20 relative. This made 27 different concrete mixtures.

The 9 mixtures of cement, fine aggregate and coarse aggregate, are as follows:

$$\frac{a}{c} = 2.00,\ b_s = \begin{cases} 0.45 \\ 0.50 \\ 0.55 \end{cases}$$

$$\frac{a}{c} = 2.50,\ b_s = \begin{cases} 0.45 \\ 0.50 \\ 0.55 \end{cases}$$

$$\frac{a}{c} = 3.00,\ b_s = \begin{cases} 0.45 \\ 0.50 \\ 0.55 \end{cases}$$

The corresponding proportions by weight are contained in table 2. No. 2 cement, no. 1 sand, and no. 3 crushed limestone were used.

TABLE 2.—*Proportions of all mixtures by weight*

Absolute volume		Proportions by weight		
b_s	$\frac{a}{c}$	Cement	Fine aggregate	Coarse aggregate
0.45	2.00	1	1.63	2.10
.45	2.50	1	2.03	2.45
.45	3.00	1	2.44	2.80
.50	2.00	1	1.63	2.57
.50	2.50	1	2.03	3.00
.50	3.00	1	2.44	3.43
.55	2.00	1	1.63	3.14
.55	2.50	1	2.03	3.66
.55	3.00	1	2.44	4.18

RESULTS OBTAINED IN FIRST GROUP OF TESTS

Table 3 shows the results of the density determinations from which the concrete-voids curves were drawn. This tabulation is an example of the data required in drawing concrete-voids curves.

Table 4 is a summary of all data collected in this group of tests. This table contains average values for each mixture. The individual values from which these averages were obtained are available.

Table 5 shows the effect of $\frac{a}{c}$, b_s and relative water content, w, on the compressive and flexural strength of the concrete.

Table 6 is a tabulation of the slumps of the 9 different mixtures for each of the 3 relative water contents.

TABLE 3.—*Concrete-voids determinations*

$\frac{a}{c}=2.00 \quad b_s=0.45$

Weight of water	Total weight of materials	Weight of materials in mold	Volume of batch	Density of concrete	Voids		
					Water	Air	Total
Pounds	*Pounds*	*Pounds*	*Cubic feet*				
2.50	36.531	24.039	0.3089	0.6315	0.126	0.2425	0.3685
2.75	36.781	25.566	.2925	.667	.147	.186	.333
3.00	37.031	26.934	.2795	.6975	.168	.1345	.3025
3.125	37.156	28.560	.2636	.737	.186	.075	.263
3.25	37.281	29.566	.2563	.761	.199	.040	.239
3.50	37.531	29.773	.2563	.761	.215	.024	.239
3.75	37.781	29.687	.2589	.753	.228	.019	.247
4.00	38.031	29.605	.2612	.747	.245	.008	.254
4.25	38.281	29.578	.2631	.742	.255	.003	.258

$\frac{a}{c}=2.5 \quad b_s=0.45$

2.75	36.589	25.781	.2885	.676	.149	.175	.324
3.00	36.839	27.836	.2691	.725	.175	.100	.275
3.25	37.089	29.348	.2569	.759	.199	.042	.241
3.375	37.214	29.476	.2567	.759	.207	.034	.241
3.50	37.339	29.594	.2565	.761	.215	.024	.239
3.50	37.339	29.648	.2564	.761	.215	.024	.239
3.75	37.589	29.652	.2577	.757	.229	.014	.243
4.00	37.839	29.508	.2607	.748	.242	.010	.252
4.25	38.089	29.516	.2623	.743	.256	.001	.257

$\frac{a}{c}=3.00 \quad b_s=0.45$

2.75	36.445	24.918	.2973	.656	.145	.201	.346
3.00	36.695	26.109	.2857	.682	.165	.153	.318
3.25	36.945	29.136	.2578	.756	.198	.046	.244
3.50	37.195	29.461	.2566	.760	.214	.026	.240
3.75	37.445	29.547	.2576	.757	.229	.014	.243
4.00	37.695	29.422	.2605	.749	.242	.009	.251
4.25	37.945	29.414	.2622	.7435	.256	.0005	.2565

$\frac{a}{c}=2.00 \quad b_s=0.50$

2.50	36.494	24.695	.3000	.650	.130	.220	.350
2.75	36.744	26.226	.2852	.684	.151	.163	.314
3.00	36.994	29.883	.2517	.775	.186	.039	.225
3.125	37.119	30.020	.2517	.776	.195	.029	.224
3.25	37.244	30.000	.2524	.773	.202	.025	.227
3.50	37.494	30.121	.2536	.769	.217	.014	.231
3.75	37.744	29.828	.2573	.758	.229	.013	.242

$\frac{a}{c}=2.50 \quad b_s=0.50$

2.50	36.320	24.601	.3001	.650	.130	.220	.350
2.75	36.570	25.840	.2873	.679	.150	.171	.321
3.00	36.820	29.043	.2577	.757	.182	.061	.243
3.125	36.945	29.719	.2527	.772	.194	.034	.228
3.25	37.070	29.875	.2523	.773	.202	.025	.227
3.50	37.320	29.746	.2551	.765	.215	.020	.235
3.75	37.570	29.789	.2564	.761	.230	.009	.239

$\frac{a}{c}=3.00 \quad b_s=0.50$

2.50	36.189	24.309	.3027	.644	.129	.227	.356
2.75	36.439	25.914	.2855	.683	.150	.167	.317
3.00	36.689	28.976	.2574	.758	.183	.059	.242
3.125	36.814	29.398	.2546	.766	.192	.042	.234
3.25	36.939	29.668	.2531	.771	.202	.027	.229
3.50	37.189	29.734	.2543	.7675	.216	.0165	.2325
3.75	37.439	29.668	.2565	.7505	.230	.0095	.2395

$\frac{a}{c}=2.00 \quad b_s=0.55$

2.50	36.495	25.715	.2885	.677	.135	.188	.323
2.75	36.745	30.125	.2480	.787	.173	.040	.213
2.875	36.860	30.242	.2478	.788	.181	.031	.212
3.00	36.995	30.582	.2459	.793	.192	.015	.207
3.25	37.245	30.660	.2470	.790	.206	.004	.210
3.50	37.495	30.375	.2509	.778	.219	.003	.222

TABLE 3.—*Concrete-voids determinations*—Continued

$\frac{a}{c}=2.50 \quad b_s=0.55$

Weight of water	Total weight of materials	Weight of materials in mold	Volume of batch	Density of concrete	Voids		
					Water	Air	Total
Pounds	*Pounds*	*Pounds*	*Cubic feet*				
2.50	36.298	26.234	.2808	.695	.139	.166	.305
2.75	36.548	29.516	.2517	.776	.171	.053	.224
2.875	36.673	30.027	.2483	.786	.181	.033	.214
3.00	36.798	30.074	.2488	.784	.189	.027	.216
3.00	36.789	30.187	.2478	.787	.189	.024	.213
3.25	37.048	30.258	.2489	.784	.204	.012	.216
3.50	37.298	30.265	.2497	.780	.220	.000	.220

$\frac{a}{c}=3.00 \quad b_s=0.55$

2.50	36.181	25.617	.2871	.680	.135	.185	.320
2.75	36.431	28.328	.2615	.746	.164	.090	.254
2.875	36.556	30.059	.2472	.789	.182	.029	.211
2.875	36.556	29.406	.2527	.772	.178	.050	.228
3.00	36.681	29.957	.2489	.784	.188	.018	.216
3.00	36.681	30.164	.2473	.789	.190	.021	.211
3.25	36.931	30.156	.2489	.784	.204	.012	.216
3.50	37.181	30.023	.2518	.774	.218	.008	.226

Table 7 shows the values and changes in values of W_c and V_c at maximum density or basic water content for the different values of $\frac{a}{c}$ and b_s.

Table 8 shows the densities taken from the concrete-voids curves and the densities as determined for the strength specimens made with corresponding mixtures.

Table 9 shows the average of individual percentage variations in strength from the arithmetic mean of each set of specimens made with each mixture.

Figure 3 shows, for each value of $\frac{a}{c}$, the concrete-voids curve for each of the three values of b_s. These curves are replotted in figure 4 which shows for each value of b_s the concrete-voids curve for each value of $\frac{a}{c}$.

Figure 5 shows the effect of variations in $\frac{a}{c}$, b_s, and relative water content on the compressive and flexural strength of concrete. Each point shown on the curve is the average of 6 breaks (3 breaks for each of the 2 beams in the case of flexure.).

Figure 6 shows the relation of the water-cement ratio to $\frac{a}{c}$ and b_s for the 27 mixtures used.

Figures 7 and 8 show the effect of the water-cement ratio on the compressive and flexural strength of the concrete. Each point on these figures is the average of 6 breaks.

Figure 9 consists of photographs showing the slumped concrete for each mixture and showing the beam breaks with the exposed particles of coarse aggregate on one of the broken ends.

RESULTS OF FIRST GROUP OF TESTS DISCUSSED

The two outstanding results developed by these tests are: For a particular value of $\frac{a}{c}$ a relation exists between the values of b_s and the value of W_c and V_c for basic water content. The same relation likewise exists between the values of b_s and the points corresponding to other relative water contents computed from the basic. This relation is shown in figure 3. In each figure the points of corresponding relative

TABLE 4.—*Summary of data from first group of tests*

$\frac{a}{c}$	b_s	Relative water content	Data from concrete-voids determinations [1]					Data from strength specimens [2]																$\frac{W_c}{c}$	Gallons of water per sack of cement	Sacks of cement per cubic yard of concrete	$\frac{c}{V_c+c}$
								Cylinders								Beams											
			Volume of batch	Voids: Water	Voids: Air	Voids: Total	Density	Volume of batch	Voids: Water	Voids: Air	Voids: Total	Density	Compressive strength	Average of individual percentage variations from arithmetic mean	Maximum spread in strength	Volume of batch	Voids: Water	Voids: Air	Voids: Total	Density	Flexural strength	Average of individual percentage variations from arithmetic mean	Maximum spread in strength				
			Cubic feet					*Cubic feet*					*Lbs. per sq. in.*		*Lbs. per sq. in.*	*Cubic feet*					*Lbs. per sq. in.*		*Lbs. per sq. in.*				
2.00	0.45	1.0	0.256	0.2045	0.0335	0.238	0.762	0.255	0.205	0.030	0.235	0.765	4,716	10.0	1,217	1.033	0.203	0.042	0.245	0.755	771	8.3	266	1.47	5.11	8.12	0.373
2.00	.45	1.1	.2575	.225	.0175	.2425	.7575	.256	.226	.013	.239	.761	4,432	3.0	410	1.038	.223	.026	.249	.751	733	4.8	123	1.63	5.66	8.07	.368
2.00	.45	1.2	.261	.2455	.0065	.252	.748	.260	.246	.002	.248	.752	3,861	6.2	714	1.046	.244	.010	.254	.746	690	6.7	137	1.80	6.24	7.97	.356
2.50	.45	1.0	.256	.2065	.0315	.238	.762	.254	.208	.024	.232	.768	3,546	3.9	577	1.027	.206	.033	.239	.761	723	3.5	77	1.73	6.02	6.98	.341
2.50	.45	1.1	.2575	.227	.0155	.2425	.7575	.256	.229	.009	.238	.762	3,235	3.0	287	1.027	.227	.016	.243	.757	694	2.5	73	1.92	6.66	6.93	.334
2.50	.45	1.2	.2605	.248	.0035	.2515	.7485	.259	.249	−.002	.247	.753	2,721	6.1	505	1.048	.247	.009	.256	.744	648	6.4	127	2.12	7.36	6.84	.323
3.00	.45	1.0	.2565	.2105	.0295	.240	.760	.254	.216	.018	.234	.766	2,951	2.5	346	1.029	.214	.026	.240	.760	620	7.8	162	2.06	7.16	6.09	.309
3.00	.45	1.1	.2585	.2315	.0145	.246	.754	.257	.237	.004	.241	.759	2,544	2.7	191	1.049	.232	.024	.256	.744	552	6.4	83	2.28	7.92	6.03	.301
3.00	.45	1.2	.262	.2525	.004	.2565	.7435	.261	.253	.000	.253	.747	1,807	4.1	287	1.043	.254	−.001	.253	.747	490	4.9	87	2.48	8.63	5.94	.287
2.00	.50	1.0	.251	.1935	.0295	.223	.777	.248	.196	.017	.213	.787	4,782	5.4	782	1.012	.193	.036	.229	.771	766	2.0	45	1.50	5.22	7.58	.380
2.00	.50	1.1	.2535	.213	.0175	.2305	.7695	.251	.215	.008	.223	.777	3,975	4.2	672	1.029	.210	.030	.240	.760	773	2.2	66	1.67	5.80	7.49	.366
2.00	.50	1.2	.2565	.232	.0075	.2395	.7605	.256	.233	.004	.237	.763	3,295	7.6	693	1.019	.233	.001	.234	.766	674	8.3	272	1.84	6.40	7.35	.348
2.50	.50	1.0	.252	.1985	.0285	.227	.773	.250	.201	.018	.219	.781	3,760	3.1	294	1.004	.199	.024	.223	.777	696	2.6	65	1.81	6.28	6.45	.336
2.50	.50	1.1	.254	.2185	.013	.2315	.7685	.252	.220	.005	.225	.775	2,958	4.7	495	1.030	.216	.026	.242	.758	600	8.3	167	2.00	6.95	6.39	.328
2.50	.50	1.2	.257	.238	.002	.240	.760	.256	.240	−.003	.237	.763	2,105	3.9	375	1.032	.237	.006	.243	.757	529	4.1	54	2.21	7.67	6.30	.314
3.00	.50	1.0	.253	.202	.027	.229	.771	.252	.203	.024	.227	.773	2,478	3.4	361	1.017	.201	.032	.233	.767	571	6.1	141	2.11	7.32	5.59	.298
3.00	.50	1.1	.257	.222	.014	.236	.764	.254	.225	.006	.231	.769	2,011	3.6	184	1.031	.221	.021	.242	.758	492	4.6	65	2.35	8.17	5.55	.292
3.00	.50	1.2	.259	.2425	.0035	.246	.754	.258	.244	−.001	.243	.757	1,290	8.1	308	1.029	.244	−.002	.242	.758	410	7.0	103	2.59	8.98	5.47	.279
2.00	.55	1.0	.246	.1815	.025	.2065	.7935	.245	.182	.021	.203	.797	4,314	9.8	1,622	1.012	.177	.052	.229	.771	766	4.9	156	1.53	5.33	6.91	.369
2.00	.55	1.1	.247	.1995	.011	.2105	.7895	.247	.200	.010	.210	.790	3,544	7.0	666	1.010	.195	.032	.227	.773	692	3.8	111	1.70	5.89	6.84	.359
2.00	.55	1.2	.2505	.218	.003	.221	.779	.250	.218	.002	.220	.780	3,061	6.2	576	1.010	.216	.012	.228	.772	675	5.5	111	1.88	6.52	6.76	.345
2.50	.55	1.0	.248	.1875	.025	.2125	.7875	.246	.189	.017	.206	.794	3,514	5.5	803	.997	.186	.031	.217	.783	684	3.7	86	1.86	6.48	5.89	.330
2.50	.55	1.1	.249	.2065	.0095	.216	.784	.248	.207	.006	.213	.787	2,946	9.2	690	1.014	.202	.028	.230	.770	605	7.9	147	2.06	7.15	5.85	.321
2.50	.55	1.2	.252	.225	.000	.225	.775	.252	.225	−.001	.224	.776	1,864	5.1	396	1.007	.225	.000	.225	.775	507	3.0	54	2.27	7.89	5.77	.307
3.00	.55	1.0	.248	.1905	.023	.2135	.7865	.247	.192	.017	.209	.791	2,776	4.3	355	1.010	.187	.040	.227	.773	581	7.1	141	2.17	7.53	5.14	.297
3.00	.55	1.1	.250	.2095	.011	.2205	.7795	.249	.210	.007	.217	.783	1,991	6.3	432	1.019	.206	.027	.233	.767	480	3.6	62	2.40	8.35	5.09	.287
3.00	.55	1.2	.254	.2285	.004	.2325	.7675	.252	.231	−.006	.225	.775	1,353	4.4	241	1.015	.228	.003	.231	.769	384	8.5	110	2.66	9.25	5.03	.278

[1] Taken from concrete-voids curves.

[2] Each value is average of 6 values except beam densities and voids which are averages of 2 values.

TABLE 5.—*Effect of $\frac{a}{c}$, b_s, and relative water content, w, on the compressive and flexural strength of concrete*

WATER CONTENT VARIABLE

$\frac{a}{c}$	b_s	Basic		$w=1.10$				$w=1.20$			
		Compressive	Flexural	Compressive	Change from basic	Flexural	Change from basic	Compressive	Change from 1.10 relative	Flexural	Change from 1.10 relative
		Pounds per sq. in.	*Pounds per sq. in.*	*Pounds per sq. in.*	*Pounds per sq. in.*	*Pounds per sq. in.*	*Pounds per sq. in.*	*Pounds per sq. in.*	*Pounds per sq. in.*	*Pounds per sq. in.*	*Pounds per sq. in.*
2.0	0.45	4,716	771	4,432	−284	733	−38	3,861	−571	690	−43
2.5	.45	3,546	723	3,235	−311	694	−29	2,721	−514	648	−46
3.0	.45	2,951	620	2,544	−407	552	−68	1,807	−737	490	−62
2.0	.50	4,782	766	3,975	−807	773	−93	3,295	−680	674	−99
2.5	.50	3,760	696	2,958	−802	600	−96	2,105	−853	529	−71
3.0	.50	2,478	571	2,011	−467	492	−79	1,290	−721	410	−82
2.0	.55	4,314	766	3,544	−770	692	−74	3,061	−483	675	−17
2.5	.55	3,514	684	2,946	−568	605	−79	1,864	−1,082	507	−98
3.0	.55	2,776	581	1,991	−785	480	−101	1,353	−638	384	−96
Average					−589		−73		−698		−68

SAND-CEMENT RATIO VARIABLE

b_s	Relative water content, w	$\frac{a}{c}=2.0$		$\frac{a}{c}=2.5$				$\frac{a}{c}=3.0$			
		Compressive	Flexural	Compressive	Change from $\frac{a}{c}=2.0$	Flexural	Change from $\frac{a}{c}=2.0$	Compressive	Change from $\frac{a}{c}=2.5$	Flexural	Change from $\frac{a}{c}=2.5$
		Pounds per sq. in.	*Pounds per sq. in.*	*Pounds per sq. in.*	*Pounds per sq. in.*	*Pounds per sq. in.*	*Pounds per sq. in.*	*Pounds per sq. in.*	*Pounds per sq. in.*	*Pounds per sq. in.*	*Pounds per sq. in.*
0.45	1.0	4,716	771	3,546	−1,170	723	−48	2,951	−595	620	−103
.45	1.1	4,432	733	3,235	−1,197	694	−39	2,544	−691	552	−142
.45	1.2	3,861	690	2,721	−1,140	648	−42	1,807	−914	490	−158
.50	1.0	4,782	766	3,760	−1,022	696	−70	2,478	−1,282	571	−125
.50	1.1	3,975	773	2,958	−1,017	600	−173	2,011	−947	492	−108
.50	1.2	3,295	674	2,105	−1,190	529	−145	1,290	−815	410	−119
.55	1.0	4,314	766	3,514	−800	684	−82	2,776	−738	581	−103
.55	1.1	3,544	692	2,946	−598	605	−87	1,991	−955	480	−125
.55	1.2	3,061	675	1,864	−1,197	507	−168	1,353	−511	384	−123
Average					−1,037		−95		−828		−123

TABLE 5.—*Effect of $\frac{a}{c}$, b_s, and relative water content, w, on the compressive and flexural strength of concrete*—Continued

COARSE AGGREGATE CONTENT VARIABLE

Relative water content, w	$\frac{a}{c}$	$b_s=0.45$ Compressive	$b_s=0.45$ Flexural	$b_s=0.50$ Compressive	$b_s=0.50$ Change from $b_s=0.45$	$b_s=0.50$ Flexural	$b_s=0.50$ Change from $b_s=0.45$	$b_s=0.55$ Compressive	$b_s=0.55$ Change from $b_s=0.50$	$b_s=0.55$ Flexural	$b_s=0.55$ Change from $b_s=0.50$
		Pounds per sq. in.	*Pounds per sq. in.*	*Pounds per sq. in.*	*Pounds per sq. in.*	*Pounds per sq.-in.*	*Pounds per sq. in.*	*Pounds per sq. in.*	*Pounds per sq. in.*	*Pounds per sq. in.*	*Pounds per sq. in.*
1.0	2.0	4,716	771	4,782	+66	766	−5	4,314	−468	766	0
1.1	2.0	4,432	733	3,975	−457	773	+40	3,544	−431	692	−81
1.2	2.0	3,861	690	3,295	−566	674	−16	3,061	−234	675	+1
1.0	2.5	3,546	723	3,760	+114	676	−27	3,514	−246	684	−12
1.1	2.5	3,235	694	2,958	−277	600	−94	2,946	−12	605	+5
1.2	2.5	2,721	648	2,105	−616	529	−119	1,864	−241	507	−22
1.0	3.0	2,951	620	2,478	−473	571	−49	2,776	+298	581	+10
1.1	3.0	2,544	552	2,011	−533	492	−60	1,991	−20	480	−12
1.2	3.0	1,807	490	1,290	−517	410	−80	1,353	+63	384	−26
Average					−362		−46		−143		−16

TABLE 6.—*Tabulation of slumps for all mixtures*

$\frac{a}{c}$	b_s	Slump in inches for relative water content of [1]— 1.00	1.10	1.20
2.00	0.45	1.5	5.0	7.0
	.50	2.5	5.5	7.0
	.55	1.5	4.5	6.5
2.50	.45	2.0	5.0	7.5
	.50	1.5	4.5	7.5
	.55	1.5	5.0	6.5
3.00	.45	1.0	4.0	6.5
	.50	2.0	4.5	7.5
	.55	2.0	5.0	7.0
Average		1.7	4.7	7.0

[1] Slump tests made in accordance with A.S.T.M. specifications.

TABLE 7.—*Values and changes in values of voids V_c and water W_c at maximum density (basic water content) for different values of $\frac{a}{c}$ and b_s.*

b_s	Sand-cement ratio, $\frac{a}{c}$: 2.00 V_c	2.00 W_c	2.50 V_c	2.50 W_c	3.00 V_c	3.00 W_c
0.45	0.238	0.2045	0.238	0.2065	0.240	0.2105
.50	.223	.1935	.227	.1985	.229	.2020
.55	.2065	.1815	.2125	.1875	.2135	.1905

	Sand-cement ratio, $\frac{a}{c}$: 2.00	2.50	3.00
Change in density at basic water with b_s changing from 0.45 to 0.50	+0.015	+0.011	+0.011
Change in density at basic water with b_s changing from 0.50 to 0.55	+.0165	+.0145	+.0155
Change in water at basic with b_s changing from 0.45 to 0.50	−.0115	−.0085	−.0085
Change in water at basic with b_s changing from 0.50 to 0.55	−.012	−.011	−.0115

TABLE 8.—*Comparison of densities from concrete-voids curves with densities of strength specimens*

$\frac{a}{c}$	b_s	Relative water content	Densities: From concrete-voids curves	As determined by strength specimens for— Cylinders	Beams
2.0	0.45	1.0	0.762	0.765	0.755
2.0	.45	1.1	.7575	.761	.751
2.0	.45	1.2	.748	.751	.746
2.5	.45	1.0	.762	.768	.761
2.5	.45	1.1	.7575	.762	.757
2.5	.45	1.2	.7485	.753	.744
3.0	.45	1.0	.760	.765	.760
3.0	.45	1.1	.754	.759	.744
3.0	.45	1.2	.7435	.747	.747
2.0	.50	1.0	.777	.787	.771
2.0	.50	1.1	.7695	.777	.760
2.0	.50	1.2	.7605	.763	.766
2.5	.50	1.0	.773	.781	.777
2.5	.50	1.1	.7685	.775	.758
2.5	.50	1.2	.760	.763	.757
3.0	.50	1.0	.771	.773	.767
3.0	.50	1.1	.764	.769	.758
3.0	.50	1.2	.754	.757	.758
2.0	.55	1.0	.7935	.797	.771
2.0	.55	1.1	.7895	.790	.773
2.0	.55	1.2	.779	.780	.772
2.5	.55	1.0	.7875	.794	.783
2.5	.55	1.1	.784	.787	.770
2.5	.55	1.2	.775	.776	.775
3.0	.55	1.0	.7865	.791	.773
3.0	.55	1.1	.7795	.783	.767
3.0	.55	1.2	.7675	.775	.769

TABLE 9.—*Average of individual percentage variations in strength from arithmetic mean of 6 breaks*

$\frac{a}{c}$	b_s	Cylinders: Relative water content 1.0	1.1	1.2	Beams: Relative water content 1.0	1.1	1.2
		Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
2.0	0.45	10.0	3.0	6.2	8.3	4.8	6.7
2.5	.45	3.9	3.0	6.1	3.5	2.5	6.4
3.0	.45	2.5	2.7	4.1	7.8	6.4	4.9
2.0	.50	5.4	4.2	7.6	2.0	2.2	8.3
2.5	.50	3.1	4.7	3.9	2.6	8.3	4.1
3.0	.50	3.4	3.6	8.1	6.1	4.6	7.0
2.0	.55	9.8	7.0	6.2	4.9	3.8	5.5
2.5	.55	5.5	9.2	5.1	3.7	7.9	3.0
3.0	.55	4.3	6.3	4.4	7.1	3.6	8.5
Average		5.3	4.9	5.7	5.1	4.9	6.0
Grand average				5.3			5.3

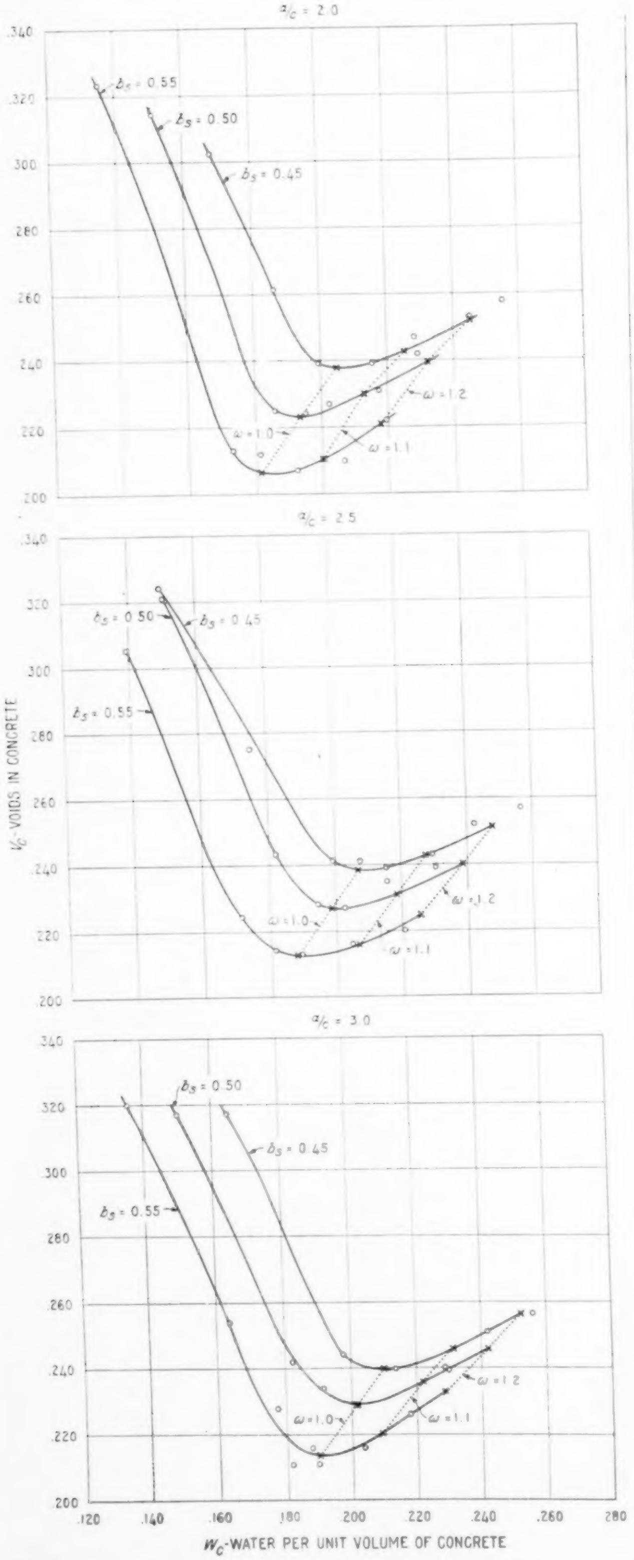


Figure 3.—Voids in Concrete Corresponding to Different Water Contents With $\frac{a}{c}$ Constant for Each Group of Curves.

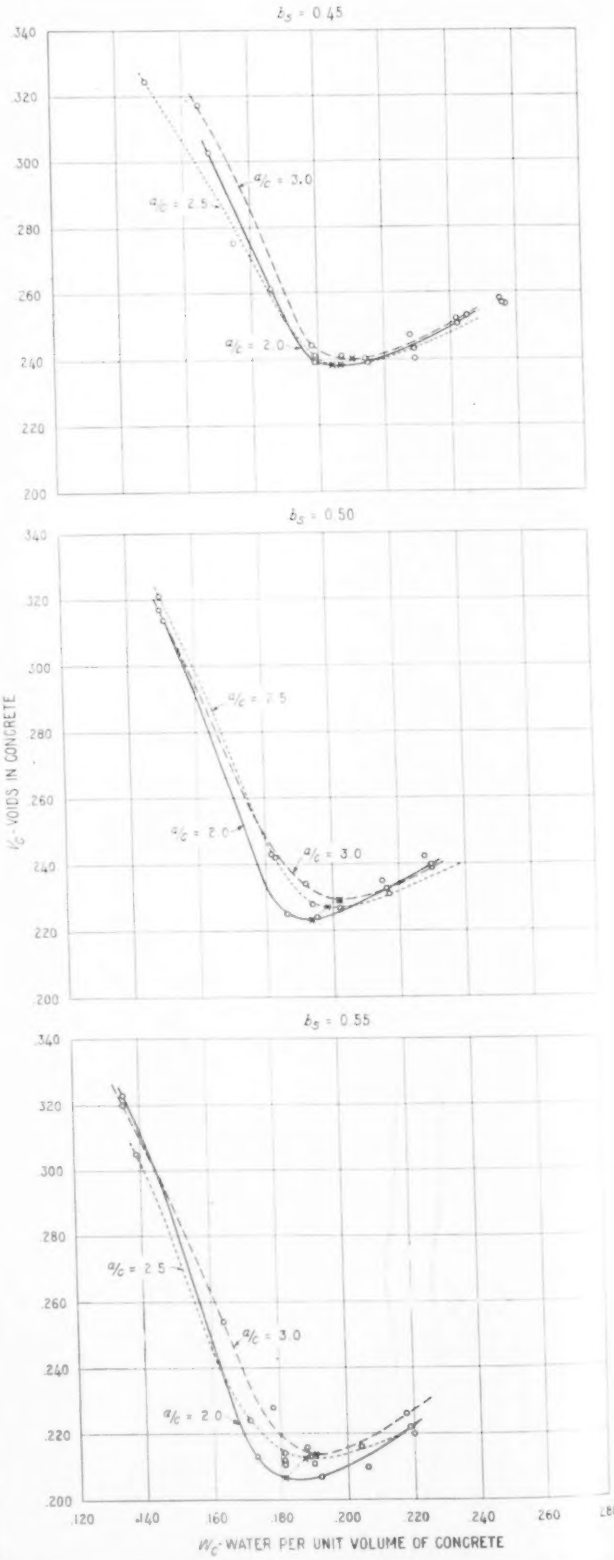


Figure 4.—Voids in Concrete Corresponding to Different Water Contents with b_s Constant for Each Group of Curves.

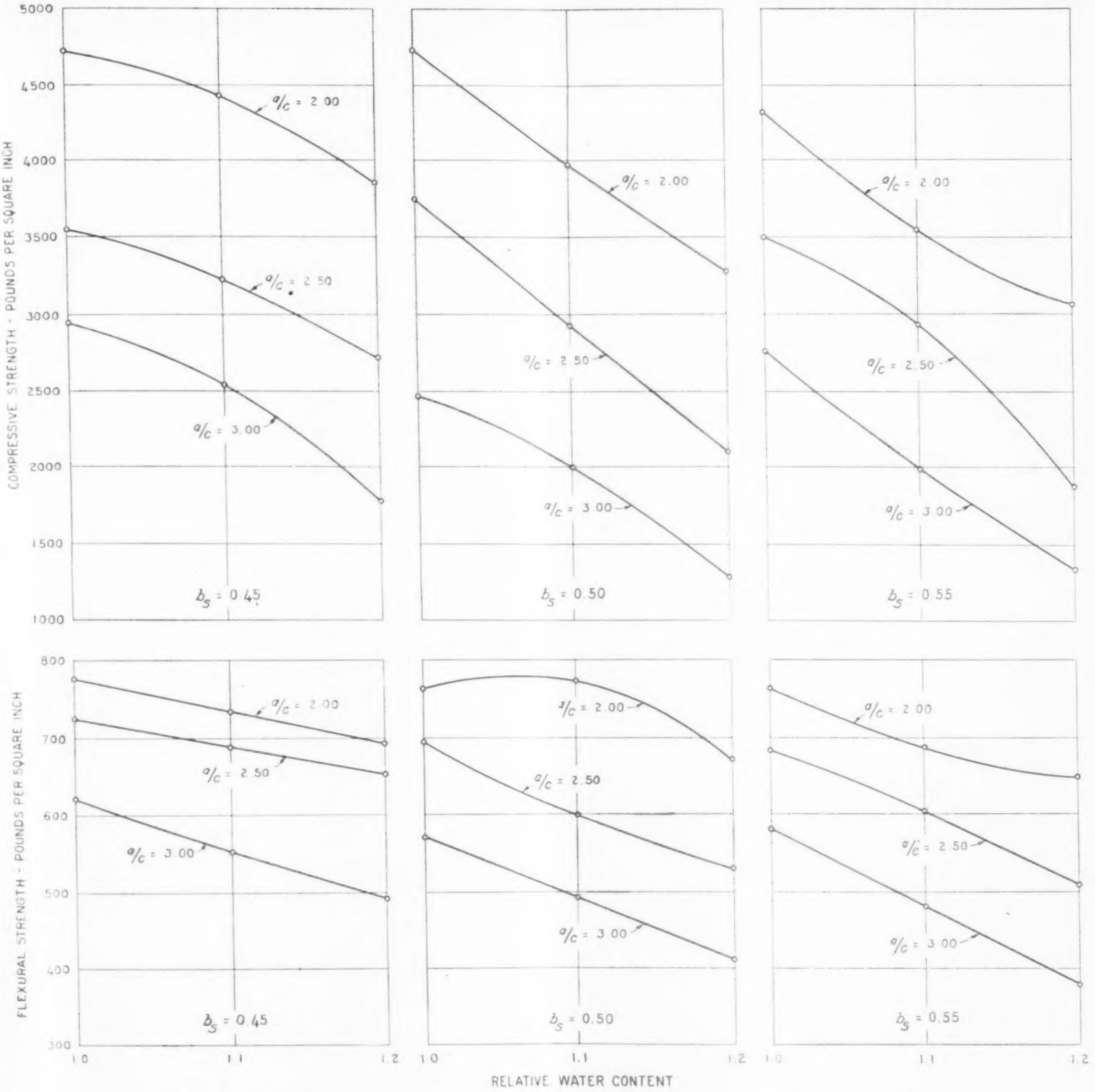


FIGURE 5.—EFFECT OF VARIATION IN $\frac{a}{c}$, b_s AND RELATIVE WATER CONTENT ON STRENGTH OF CONCRETE.

water content on the three b_s curves fall on a line that is approximately straight.

A relation exists between the values of $\frac{a}{c}$ and the points corresponding to each relative water content for each particular value of b_s. The points of basic water content are shown on the three $\frac{a}{c}$ curves for each value of b_s in figure 4. This relation is not as definite as that shown in figure 3.

For a particular relative water content the slump of the concrete is nearly constant regardless of the values of $\frac{a}{c}$ and b_s used in the mixture. The slumps of the 9 concrete mixtures for each of the 3 relative water contents, 1.00, 1.10, and 1.20, are shown in table 6. There are some variations in the slumps as shown for each relative water content. Individual slumps, however, do not vary greatly from the average. The variations are considered to be within the probable error within which the slump test can be made.

Other results shown by this test follow:

The basic water content or the amount of water required to give maximum density to a concrete mixture, may be different for every different combinations of the ingredients.

A concrete mixture having maximum density (as molded in this test by a new method designed to dupli-

54633—34——2

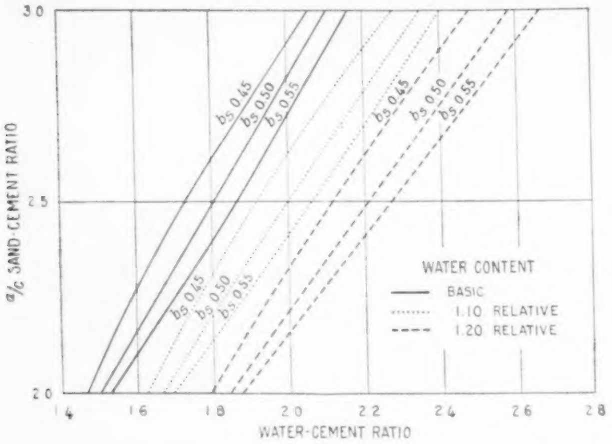


FIGURE 6.—RELATION OF WATER-CEMENT RATIO TO $\frac{a}{c}$ AND b_s.

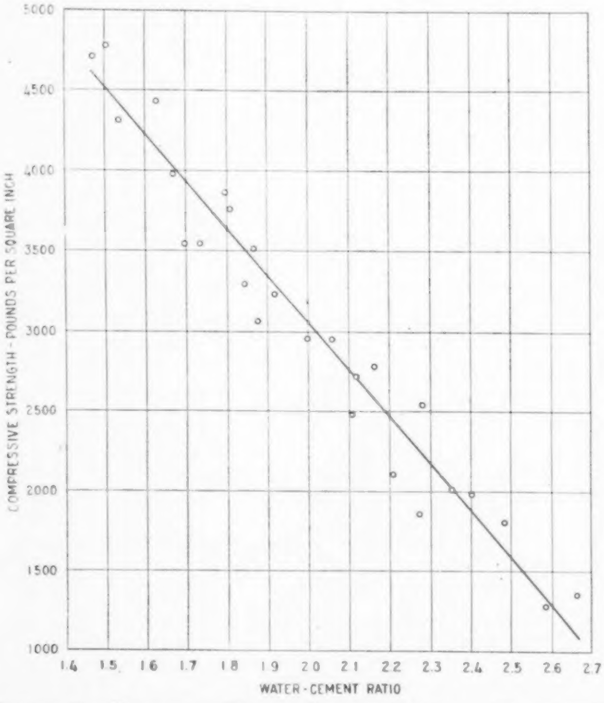


FIGURE 7.—EFFECT OF WATER-CEMENT RATIO ON COMPRESSIVE STRENGTH.

cate the density of the concrete in place in a pavement) contains both water and air voids. Combinations of the particular materials used in this test, require a value of w greater than 1.20 relative to eliminate all air voids. The slump corresponding to this relative water content of 1.20 is 7 inches.

With a fixed ratio of sand to cement the amount of water per unit volume of concrete required to give maximum density and the total voids in the mixture decreases as the coarse aggregate content of the mixture is increased. This relation is shown in figure 3 and table 7. With a given ratio of coarse aggregate to total solid volume the amount of water required to give maximum density and the total voids in the mixture increases as the ratio of sand to cement increases. The increase is slight for the range in sand and cement contents used in this test. This relation is shown in figure 4 and table 7.

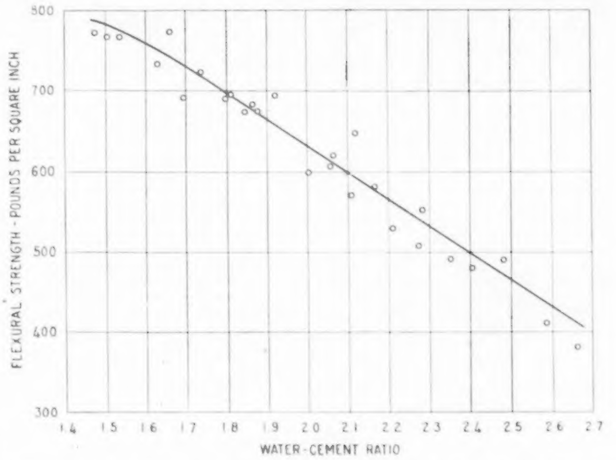


FIGURE 8.—EFFECT OF WATER-CEMENT RATIO ON FLEXURAL STRENGTH.

The density of the concrete in every strength specimen was determined immediately after the specimen was molded. The closeness with which these determinations approach the densities shown on the concrete-voids curves for the corresponding combinations of $\frac{a}{c}$, b_s, and w is shown in table 8. The strength-specimen density values are averages for 6 cylinders and for 2 beams made with each combination. There is some irregularity between the densities of the test specimens and the densities of corresponding mixtures as determined from the concrete-voids curves. These discrepancies, which are not excessive, can be accounted for in part, by the fact that the concrete-voids specimens were molded in a heavy steel cylinder mold whereas the test cylinders were molded in light cardboard molds and the beams were molded in wooden molds. The difference in the weights and types of molds may have caused a difference in the magnitude of the impacts delivered to each. The wooden molds for beams were not absolutely watertight, and it was more difficult to determine the volume of the concrete in the mold due to the large area to be struck off.

In this test (in which water contents equal to or higher than basic were used) the amount of water required to give maximum density to a particular combination of materials was found to be that water content which gave maximum strength to the concrete made with that particular combination. The strength of a concrete mixture decreased as its relative water content increased, as the value of $\frac{a}{c}$ increased and as the value of b_s increased. The results of the strength tests showing graphically the relation between strength, $\frac{a}{c}$, b_s and w are shown in figure 5. The actual variations in strength caused by variations in the values of $\frac{a}{c}$, b_s and w are shown in table 5. It should be borne in mind that changes in the values of $\frac{a}{c}$, b_s and w are accompanied by changes in the water-cement ratio. These changes are shown in table 4 for all mixtures. An analysis of this table shows that for the 9 different combinations of $\frac{a}{c}$ and b_s the average decreases in

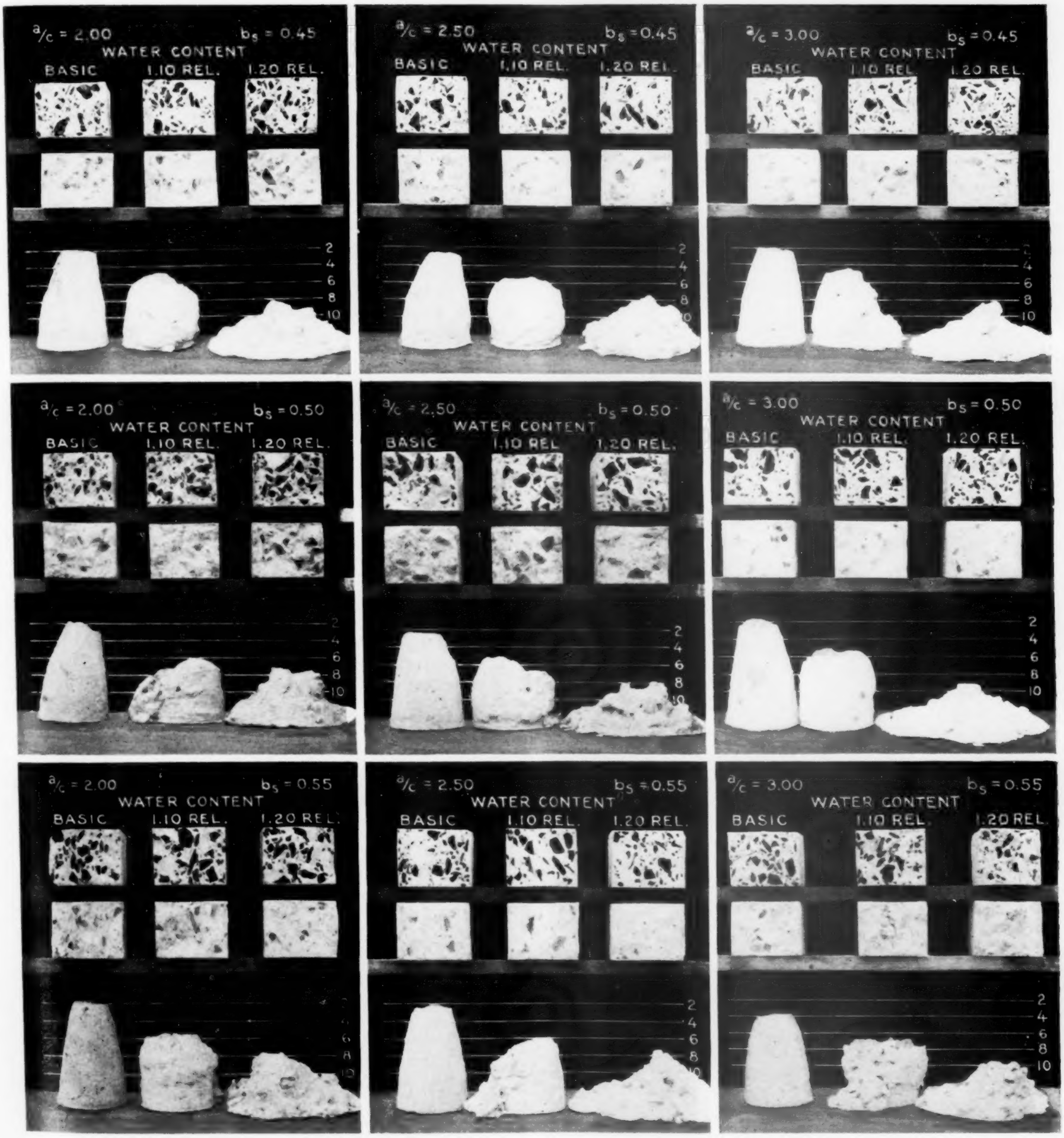


FIGURE 9.—SLUMP TEST SPECIMENS AND CORRESPONDING BEAM BREAKS FOR VALUES OF $\frac{a}{c}$, b_s AND RELATIVE WATER CONTENTS AS INDICATED. COARSE AGGREGATE HAS BEEN PAINTED ON UPPER BEAM BREAK IN EACH CASE

strengths due to increase in the relative water content are as follows:

Change in strength due to change in water content

	Pounds per square inch	Percent
From basic to 1.10 relative:		
Compression	−589	16
Flexure	−73	11
From 1.10 relative to 1.20 relative:		
Compression	−698	23
Flexure	−68	11

For the nine different combinations of b_s and w the average decreases in strength due to increase in the value of $\frac{a}{c}$ are as follows:

	Pounds per square inch	Percent
Change in $\frac{a}{c}$ from 2.00 to 2.50:		
Compression	−1,037	26
Flexure	−95	13
Change in $\frac{a}{c}$ from 2.50 to 3.00:		
Compression	−828	28
Flexure	−123	19

For the nine different combinations of w and $\frac{a}{c}$ the average decreases in strength due to increase in the value of b_s are as follows:

	Pounds per square inch	Percent
Change in b_s from 0.45 to 0.50:		
Compression	−362	11
Flexure	−46	7
Change in b_s from 0.50 to 0.55:		
Compression	−143	5
Flexure	−16	3

The results of this analysis show that with the particular materials used a change of 0.1 in the value of w, the relative water content, caused a change in strength of 589 to 698 pounds in compression and of 68 to 73 pounds in flexure. A change of 0.5 in $\frac{a}{c}$, the sand-cement ratio, caused a change in strength of 828 to 1,037 pounds in compression and of 95 to 123 pounds in flexure. A change in b_s of 0.05 caused a change in strength of 143 to 362 pounds in compression and of 16 to 46 pounds in flexure.

The results of these tests indicate the effect of varying the proportions of ingredients on the strength of concrete. The experience in expressing proportions on the basis of solid volumes was very satisfactory. Volume relations were being studied and direct expression of these relations was more convenient, in this study, than indirect expression with specific gravity as a factor influencing conclusions.

The range in the values of b_s in this test was not sufficiently great to reflect the effect of the amount of coarse aggregate on the strength of concrete. The second group of tests described in this report show this effect in concrete mixtures in which the values of b_s range from zero to the maximum.

A definite relation is shown to exist between the water-cement ratio and the strength of concrete both in compression and flexure. This relation is shown in figures 7 and 8. Each point in these figures is the average of six breaks. The points fall within a band which approaches a straight line. The width of the band is presumably due to irregularities in mixing, molding, curing, capping, and testing and not to variation in the water-cement relationship.

The strengths of concrete mixtures composed of different proportions of cement, aggregates, and water bear no direct relation to their respective densities. As an example the mixture with $\frac{a}{c}=2.00$, $b_s=0.45$, and $w=1.00$ has a density of 0.7650 and a compressive strength of 4,716 pounds per square inch; the mixture with $\frac{a}{c}=3.00$, $b_s=0.55$, and $w=1.20$ has a density of 0.7746 and a compressive strength of 1,353 pounds per square inch. The densities and corresponding strengths for all mixtures are shown in table 4. The density determination appears to have its greatest value in determining the amount of water required to give maximum density to a particular combination of materials under a particular method of placing. The strength of a particular mixture, however, can be expected to be greater with maximum density than with any other density resulting from greater amounts of water. The actual density obtained can be expected to be different for different methods of placing.

There is a relation between the cement-space ratio and the strength of concrete because this ratio involves the amount of cement. This relationship, however, is not definite like the water-cement ratio because it involves the total void space, and the voids or densities for different mixtures bear no direct relation to strength. The cement-space ratio for every mixture is shown in table 4.

The amount of water required to give maximum density to a particular combination of materials can be determined with a reasonable degree of accuracy on the basis of density determinations made by mechanical means. This is shown in table 3 and in the concrete-voids curves of figure 3. These curves are remarkably regular considering the fact that each curve is described by only a few points and each point represents but one density determination.

The mechanical method of molding concrete strength specimens is considered to be comparable with the standard hand method from the standpoint of the consistency of strength results. The data in table 9 show the average of individual percentage variations in strength from the arithmetic mean for each group of specimens for each mixture. The grand average of all these variations in all mixes is 5.3 percent for both cylinders and beams.

SECOND GROUP OF TESTS MADE

A second group of tests was made for two purposes: First, to check the relations found to exist in the first group, and second, to determine the effect of the amount of coarse aggregate in a concrete mixture on the strength of the resulting concrete. This group consisted of three series. A value of $\frac{a}{c}$ of 2.576 and a value of w of 1.10 relative, was used in every mixture in all three series. The value of b_s in series 1 and 3 was varied by increments of 0.10 and in series 2 by increments slightly greater than 0.10, from 0.00 to or slightly above the point at which the mortar was sufficient to fill the void spaces in the mass of coarse aggregate as placed in the molds. This resulted in 8 concrete-voids curves for series 1, 9 curves for series 2, and 8 curves for series 3. Strength specimens were made only with those mixtures in which the mortar was sufficient to fill the void spaces in the coarse aggregate. This resulted in 7 different mixtures for series 1 and 8 different mixtures for series 2 and 3, making 23 mixtures from which strength specimens and slump tests were made. Two different kinds of coarse aggregate and two different brands of cement were used. The same kind of sand was used in all tests. The materials used in each series are shown in table 10.

Density determinations were made and concrete-voids curves were drawn for every mixture in each series. Each curve was used in determining the basic water content for each mixture; and for determining the amount of water and the total voids for a relative water content of 1.10, which was the water content used in all

TABLE 10.—*Materials used in each series of tests*

Series	Cement	Fine aggregate	Coarse aggregate
1	No. 2	Sand, no. 1	Crushed limestone, no. 3.
2	No. 1	do	Gravel, no. 2.
3	No. 2	do	Do.

three series. These water and voids data were then used in computing the proportion of each ingredient to be used in the strength-specimen mixtures. Every mixture in which the mortar was sufficient to fill the void spaces in the course aggregate was subjected to one slump test, and three 6 by 12-inch cylinders and one 6 by 8 by 30-inch beam were made. Every point on all strength curves represents the average of 3 breaks in either compression or flexure.

RESULTS OBTAINED IN SECOND GROUP OF TESTS

Table 11 is a summary of the data from this group of tests, with the exception of the densities from which the concrete-voids curves were drawn. These data are represented by the points on the concrete-voids curves.

Table 12 shows the results of slump tests for each value of b_s in each series.

Table 13 shows the amount of water in addition to that required for the mortar that is required by the coarse aggregate at basic water content for the two types of coarse aggregate used.

Table 14 shows the water and total voids per unit volume of concrete at basic water content for the different values of b_s in each set.

Table 15 contains the mix proportions by weight for all mixtures used in strength specimens in each set.

Figures 10, 11, and 12 show the concrete-voids curves for all mixtures in each series of tests. In figure 10 the curve for the mixture with $b_s=0.70$ and in figure 11 the curve for the mixture with $b_s=0.803$ represent those mixtures in which the mortar was not sufficient to fill the void spaces in the coarse aggregate.

Figures 13 and 14 show the relation between the water-cement ratio and the compressive and flexural strengths of the concrete.

TABLE 12.—*Slump of concrete for each mixture in each series*

[$a/c=2.576$; $w=1.10$ relative]

b_s	Series 1	Series 2	Series 3
	Inches	*Inches*	*Inches*
0.0	4.5	2	5
.1	4	2.5	6
.2	4	2.5	4
.3	4.5	2.5	5
.4	4.5	2	4
.5	5	3	5.5
.6	3.5	1	5.5
.7		2.5	5.5
Average	4.5	2	5

TABLE 11.—*Summary of data from second group of tests*

	$\frac{a}{c}$	b_s	Relative water content	Data from concrete-voids determinations[1]					Data from strength specimens[2]																$\frac{W}{c}$	Gallons of water per sack of cement	Sacks of cement per cubic yard of concrete	$\frac{c}{V_v+c}$	Ratio of compressive to flexural strength
									Cylinders								Beams												
				Volume of batch	Voids: Water	Voids: Air	Voids: Total	Density	Volume of batch	Voids: Water	Voids: Air	Voids: Total	Density	Compressive strength	Average of individual percentage variations from arithmetic mean	Maximum spread in strength	Volume of batch	Voids: Water	Voids: Air	Voids: Total	Density	Flexural strength	Average of individual percentage variations from arithmetic mean	Maximum spread in strength					
				Cu. ft.					*Cu. ft.*					*Lbs. per sq. in.*		*Lbs. per sq. in.*	*Cu. ft.*					*Lbs. per sq. in.*		*Lbs. per sq. in.*					
Series 1	2.576	0.0	1.10	0.308	0.321	0.050	0.371	0.629	0.304	0.325	0.037	0.362	0.638	5,290	1.0	134	1.223	0.315	0.051	0.366	0.634	690	10.1	201	1.82	6.33	10.39	0.330	7.67
	2.576	.1	1.10	.295	.303	.038	.341	.659	.292	.306	.030	.336	.664	4,597	2.5	343	1.213	.294	.066	.360	.640	706	4.3	83	1.83	6.35	9.73	.333	6.52
	2.576	.2	1.10	.2855	.283	.036	.319	.681	.281	.288	.020	.308	.692	4,229	3.0	365	1.148	.282	.040	.322	.678	647	15.9	239	1.86	6.47	8.98	.334	6.55
	2.576	.3	1.10	.274	.261	.028	.289	.711	.271	.264	.017	.281	.719	3,992	1.7	173	1.103	.260	.035	.295	.705	657	5.0	76	1.88	6.53	8.15	.333	6.08
	2.576	.4	1.10	.264	.239	.0225	.2615	.7385	.260	.242	.009	.251	.749	3,261	2.7	227	1.058	.238	.026	.264	.736	679	2.7	48	1.94	6.73	7.27	.333	4.80
	2.576	.5	1.10	.2545	.215	.0185	.2335	.7665	.252	.216	.011	.227	.773	3,067	0.5	36	1.018	.215	.018	.233	.767	676	.8	13	2.01	6.99	6.25	.322	4.54
	2.576	.6	1.10	.2435	.186	.012	.198	.802	.243	.187	.008	.195	.805	2,299	9.9	580	.986	.184	.024	.208	.792	606	3.0	42	2.09	7.25	5.20	.314	3.79
Series 2	2.576	.000	1.10	.3055	.316	.0615	.3775	.6225	.304	.312	.062	.374	.626	2,820	8.4	612	1.228	.309	.071	.380	.620	759	1.4	30	1.78	6.14	10.27	.390	3.72
	2.576	.102	1.10	.295	.298	.0555	.3535	.6465	.291	.302	.044	.346	.654	3,312	16.5	1,530	1.189	.296	.062	.358	.642	605	1.1	18	1.84	6.34	9.62	.322	5.47
	2.576	.203	1.10	.286	.278	.0525	.3305	.6695	.283	.281	.043	.324	.676	3,787	2.5	239	1.159	.275	.063	.338	.662	621	5.9	92	1.88	6.46	8.80	.317	6.10
	2.576	.304	1.10	.2715	.253	.0395	.2925	.7075	.271	.254	.037	.291	.709	3,491	4.3	391	1.091	.252	.043	.295	.705	642	5.1	92	1.85	6.36	8.06	.321	5.44
	2.576	.404	1.10	.263	.232	.0355	.2675	.7325	.261	.234	.027	.261	.739	3,418	4.3	364	1.048	.234	.030	.264	.736	638	6.5	120	1.92	6.60	7.17	.319	5.36
	2.576	.505	1.10	.252	.2085	.0255	.234	.766	.252	.209	.023	.232	.768	3,092	2.2	158	1.025	.206	.041	.247	.753	532	6.2	84	1.98	6.85	6.20	.313	5.81
	2.576	.605	1.10	.246	.1815	.0205	.202	.798	.242	.182	.017	.199	.801	2,875	2.8	199	.994	.178	.040	.218	.782	457	2.4	29	2.07	7.13	5.17	.308	6.29
	2.576	.704	1.10	.2355	.162	.0115	.1735	.8265	.236	.161	.014	.175	.825	1,721	3.7	179	.944	.161	.014	.175	.825	348	4.1	43	2.40	8.25	3.94	.278	4.95
Series 3	2.576	.0	1.10	.308	.321	.050	.371	.629	.305	.325	.038	.363	.637	4,606	4.3	579	1.254	.318	.059	.377	.623	670	5.9	111	1.83	6.34	10.35	.330	6.87
	2.576	.1	1.10	.296	.3035	.0415	.345	.655	.295	.305	.037	.342	.658	4,227	2.5	281	1.203	.299	.056	.355	.645	597	3.7	55	1.84	6.40	9.62	.326	7.08
	2.576	.2	1.10	.285	.2805	.0375	.318	.682	.284	.282	.032	.314	.686	3,905	6.5	630	1.585	.276	.052	.328	.672	583	2.7	38	1.84	6.40	8.89	.327	6.70
	2.576	.3	1.10	.274	.261	.028	.289	.711	.275	.261	.030	.291	.709	3,738	3.0	282	1.122	.255	.042	.297	.703	520	4.9	61	1.89	6.55	8.03	.322	7.19
	2.576	.4	1.10	.264	.2375	.0245	.262	.738	.264	.238	.023	.261	.739	3,465	1.4	112	1.043	.240	.013	.253	.747	505	2.9	32	1.93	6.70	7.17	.321	6.86
	2.576	.5	1.10	.258	.221	.021	.242	.758	.258	.221	.021	.242	.758	2,586	2.0	152	1.027	.222	.016	.238	.762	561	1.9	26	2.10	7.30	6.13	.304	4.61
	2.576	.6	1.10	.245	.1915	.012	.2035	.7965	.246	.191	.014	.205	.795	2,249	1.7	106	.979	.194	.007	.201	.799	459	.1	2	2.17	7.52	5.13	.301	4.90
	2.576	.7	1.10	.242	.1815	.0095	.191	.809	.240	.183	.001	.184	.816	1,017	4.9	136	.963	.183	.004	.187	.813	305	.8	6	2.70	9.38	3.94	.270	3.33
Average															4.0								4.2						5.68

[1] Taken from concrete-voids curves.
[2] Each value is the average of 3 values except beam densities and voids which are based on 1 determination each.

TABLE 13.—*Calculations to determine the amount of water needed to lubricate the coarse aggregate in concrete mixtures at basic water content* [1]

1	2	3	4	5	6	7	8	9	10	11	12	13
b_s	Density	W_s	V_s	Air	Volume of dry materials plus absorption	Batch volume	Volume water	Volume dry coarse aggregate	Volume sand and cement	Water required for mortar	Water required for coarse aggregate	Water per cubic foot of coarse aggregate, by solid volume
GRAVEL					*Cu. ft.*	*Cu. ft.*	*Cu. ft.*	*Cu. ft.*	*Cu. ft.*	*Cu. ft.*	*Cu. ft.*	*Gallons*
0.0000	0.6290	0.2870	0.3710	0.0840	0.1901	0.3022	0.0867	0.0000	0.1901	0.0867	0.0000	0.000
.1017	.6515	.2710	.3485	.0775	.1907	.2927	.0793	.0194	.1711	.0780	.0013	.501
.2032	.6770	.2530	.3230	.0700	.1914	.2827	.0715	.0388	.1521	.0693	.0022	.424
.3040	.7105	.2300	.2895	.0595	.1921	.2704	.0622	.0582	.1331	.0607	.0015	.193
.4045	.7380	.2110	.2620	.0510	.1927	.2611	.0551	.0776	.1141	.0520	.0031	.299
.5054	.7695	.1895	.2305	.0410	.1934	.2513	.0476	.0970	.0951	.0434	.0042	.324
.6047	.8045	.1650	.1955	.0305	.1939	.2410	.0398	.1163	.0761	.0347	.0051	.327
.7039	.8300	.1470	.1700	.0230	.1946	.2345	.0344	.1357	.0571	.0261	.0083	.457
Average												.361
CRUSHED LIMESTONE												
0.0000	.6420	.2920	.3580	.0660	.1940	.3021	.0881	.0000	.1940	.0881	.0000	.000
.1000	.6640	.2750	.3360	.0610	.1942	.2926	.0805	.0194	.1746	.0793	.0011	.428
.2000	.6890	.2570	.3110	.0540	.1944	.2825	.0726	.0388	.1552	.0726	.0021	.408
.3000	.7145	.2370	.2855	.0485	.1946	.2725	.0646	.0582	.1358	.0617	.0028	.362
.4000	.7430	.2170	.2570	.0400	.1948	.2625	.0568	.0776	.1664	.0529	.0040	.384
.5000	.7725	.1950	.2275	.0325	.1951	.2526	.0483	.0970	.0970	.0440	.0052	.400
.6000	.8070	.1690	.1930	.0240	.1953	.2422	.0409	.1164	.0776	.0352	.0057	.364
Average												.394

[1] Water to lubricate coarse aggregate with b_s of 0.00 is not included in the averages shown.

The values for the water required for mortar shown in column 11 for those mixtures containing coarse aggregate are in the same ratio to the corresponding values for volume of sand and cement shown in column 10 as the ratios between similar values (in same column), for the mixture containing no coarse aggregate. The water value for the mortar mixture, from which the water values for the mortar in the concrete mixtures are computed, is obtained from the mortar-voids curve. The water required for the coarse aggregate for each mixture shown in column 12 is the difference between the corresponding water values in columns 8 and 11.

TABLE 14.—*Water and total voids per unit volume of concrete at basic water content for different values of b_s*

Series 1			Series 2			Series 3		
b_s	Water voids	Total voids	b_s	Water voids	Total voids	b_s	Water voids	Total voids
	Percent	*Percent*		*Percent*	*Percent*		*Percent*	*Percent*
0.0	0.292	0.358	0.00	0.287	0.371	0.0	0.292	0.358
.1	.275	.336	.102	.271	.3485	.1	.276	.336
.2	.257	.311	.203	.253	.323	.2	.255	.308
.3	.237	.2855	.304	.230	.2895	.3	.2375	.284
.4	.217	.257	.404	.211	.262	.4	.216	.255
.5	.195	.2275	.505	.1895	.2305	.5	.201	.235
.6	.169	.193	.605	.165	.1955	.6	.174	.1975
			.704	.147	.170	.7	.165	.185

TABLE 15.—*Proportions by weight for all mixtures used in strength specimens in each series*

Series 1				Series 2				Series 3			
b_s	Proportions by weight			b_s	Proportions by weight			b_s	Proportions by weight		
	Cement	Fine aggregate	Coarse aggregate		Cement	Fine aggregate	Coarse aggregate		Cement	Fine aggregate	Coarse aggregate
0.0	1.00	2.09	0.00	0.000	1.00	2.08	0.00	0.0	1.00	2.09	0.00
.1	1.00	2.09	.34	.102	1.00	2.08	.32	.1	1.00	2.09	.32
.2	1.00	2.09	.76	.203	1.00	2.08	.73	.2	1.00	2.09	.72
.3	1.00	2.09	1.31	.304	1.00	2.08	1.25	.3	1.00	2.09	1.24
.4	1.00	2.09	2.04	.404	1.00	2.08	1.95	.4	1.00	2.09	1.93
.5	1.00	2.09	3.06	.505	1.00	2.08	2.92	.5	1.00	2.09	2.89
.6	1.00	2.09	4.59	.605	1.00	2.08	4.39	.6	1.00	2.09	4.33
				.704	1.00	2.08	6.81	.7	1.00	2.09	6.74

Figures 15 and 16 show the relation between the values of b_s and the compressive and flexural strength of the concrete.

Figure 17 shows photographs of the slumped concrete for each mixture and the beam breaks with the exposed particles of coarse aggregate painted.

RESULTS OF SECOND GROUP OF TESTS DISCUSSED

The two outstanding results shown in the first group of tests are repeated in these tests. They are as follows:

For a particular value of $\frac{a}{c}$ a relation exists between the values of b_s and the points of basic water content. The same relation likewise exists between the values of b_s and the points of other relative water contents (1.10 relative in these tests), which are computed from the basic. This relation is shown in figures 10, 11, and 12. In each of these figures the point of basic and the point of 1.10 relative water content on each b_s curve fall on lines that are approximately straight.

For a particular relative water content, 1.10 in these tests, the slump of every concrete mixture composed of the same kinds of materials is nearly constant regardless of the value of b_s for the mixture. The results of the slump test for each mixture in each series are shown in table 12. Figure 17 shows the slumped concrete for all mixtures in each series. The consistency of the slump-relative water relation is demonstrated by the fact that in each series the slump of the mixture containing no coarse aggregate is approximately the same as the slump of the mixture containing the maximum amount of coarse aggregate.

Other interesting results shown by these tests follow:

The point of basic water content may be different for every different combination of materials. For a given value of $\frac{a}{c}$ the amount of water and the resulting voids decrease as b_s increases. This is shown in table 14 and in figures 10, 11, and 12. The amount of water required to give maximum density to combinations of different materials having the same values of $\frac{a}{c}$ and b_s may vary for different brands and gradations of cement and for different kinds and gradations of fine and coarse

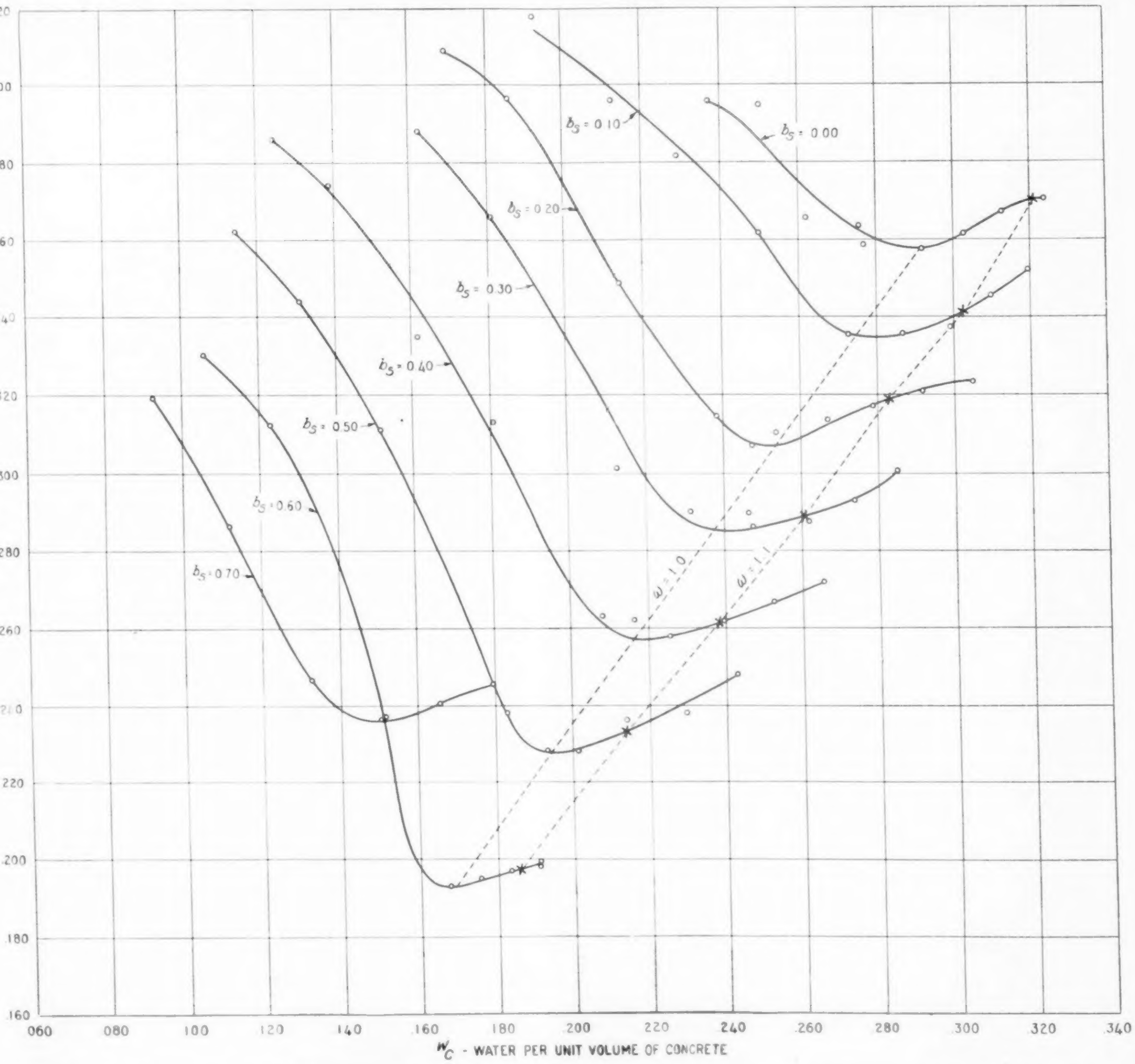


FIGURE 10.—CONCRETE-VOIDS CURVES FOR FIRST SERIES (VARYING VALUES OF b_s AND CONSTANT VALUE OF $\frac{a}{c}=2.576$).

aggregate. This is shown in table 14. The water and the total voids vary for similar proportions in the different series.

The concrete mixtures having maximum density as placed in the mold in this test contained both water and air voids.

The well-known relation between the water-cement ratio and the strength of concrete both in compression and flexure is shown in figures 13 and 14. The relationship does not approach a straight line as closely as in the first series of tests.

No relation is apparent between densities and strengths of different concrete mixtures. However, table 11 shows that the density increases and the strength decreases as the value of b_s increases for each series.

Mixtures with the same relative water content and the same values of $\frac{a}{c}$ and b_s may vary considerably in slump, depending on the characteristics of the ingredients. Table 12 shows an average slump of 5 inches for series 3 and 2 inches for series 2. The same kind of fine and coarse aggregate was used in both series, but the brand of cement was different. There is also a difference in the average slumps of series 1 and 3 of ½ inch. Here the only variation in the kind of materials used was in the coarse aggregate. Series 1 had an average slump of 4½ inches, against a slump of 2 inches for series 2. Different brands of cement and different kinds of coarse aggregate were used in these series. It appears from this test that the characteristics of the cement play an important part in affecting the slump or workability at any particular relative water content. The influence of the fine aggregate or the combination of fine aggregate and cement on the slump is not shown since the same kind of fine aggregate was used in all series.

In these tests the compressive and flexural strength of concrete decreased as the value of b_s increased. This is shown in figures 15 and 16. There are exceptions to this trend, however. It is believed that these exceptions are due to the inconsistencies inherent in

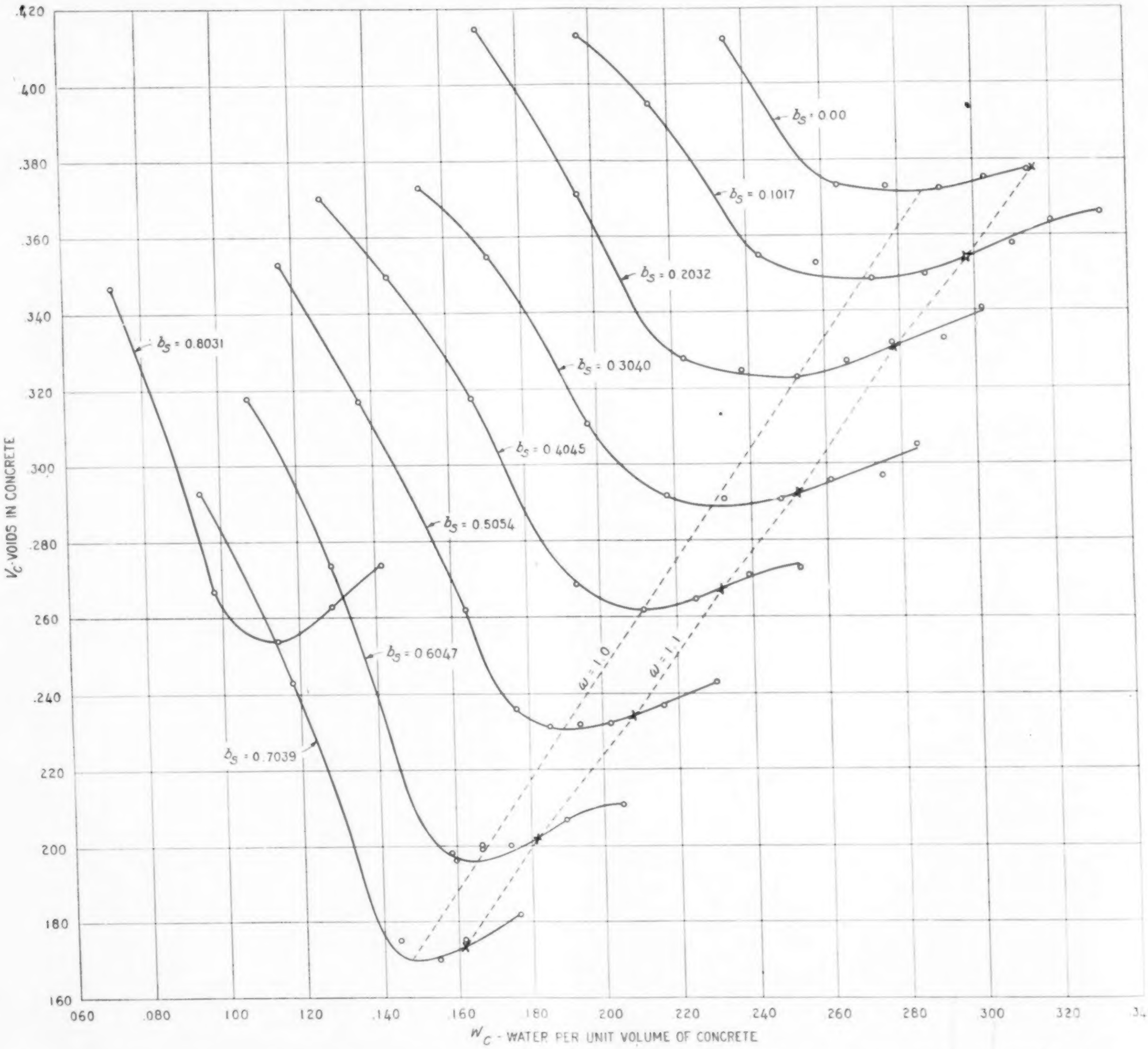


FIGURE 11.—CONCRETE-VOIDS CURVES FOR SECOND SERIES (VARYING VALUES OF b_s AND CONSTANT VALUE OF $\frac{a}{c}=2.576$)

testing work. As an example, figure 15 shows low compressive strengths for mixtures of series 2 with values of b_s of 0.00 and 0.10. Table 11 shows that for these particular mixtures the maximum spread in the strengths and the average of the variations from the mean are excessive. One of the cylinders with a value of b_s of 0.10 had a strength of 4,033 pounds. A poor cylinder in the group brought the average down. With the exception of these two mixtures the strength-b_s relation is more consistent for the cylinders than for the beams. The corresponding values of $\frac{W_c}{c}$ for all values of b_s are shown in table 11.

The relation between the kind of cement used and the strength of the concrete is shown in table 11. The slump of the concrete in series 1 and 3 was 4½ and 5 inches, respectively. The slump of the concrete in series 2 was 2 inches. Had series 1 and 3 been made with a relative water content such as to give a 2-inch slump the strengths for these series would doubtless be much higher and would be considerably in excess of the strengths of corresponding mixtures in series 2. The same aggregates but different brands of cement were used in series 2 and 3. The same brand of cement but different coarse aggregates were used in series 1 and 3. Had these brands of cement been used with other kinds of fine aggregate the resulting slumps and strengths might have been still different.

The proportions by weight of all mixtures are shown in table 15. The proportions of mixtures having similar values of b_s differ somewhat in the different series due to differences in the specific gravities of the materials.

In these tests no definite relation was found between the compressive and flexural strengths of specimens composed of the same mixtures. Table 11 shows the

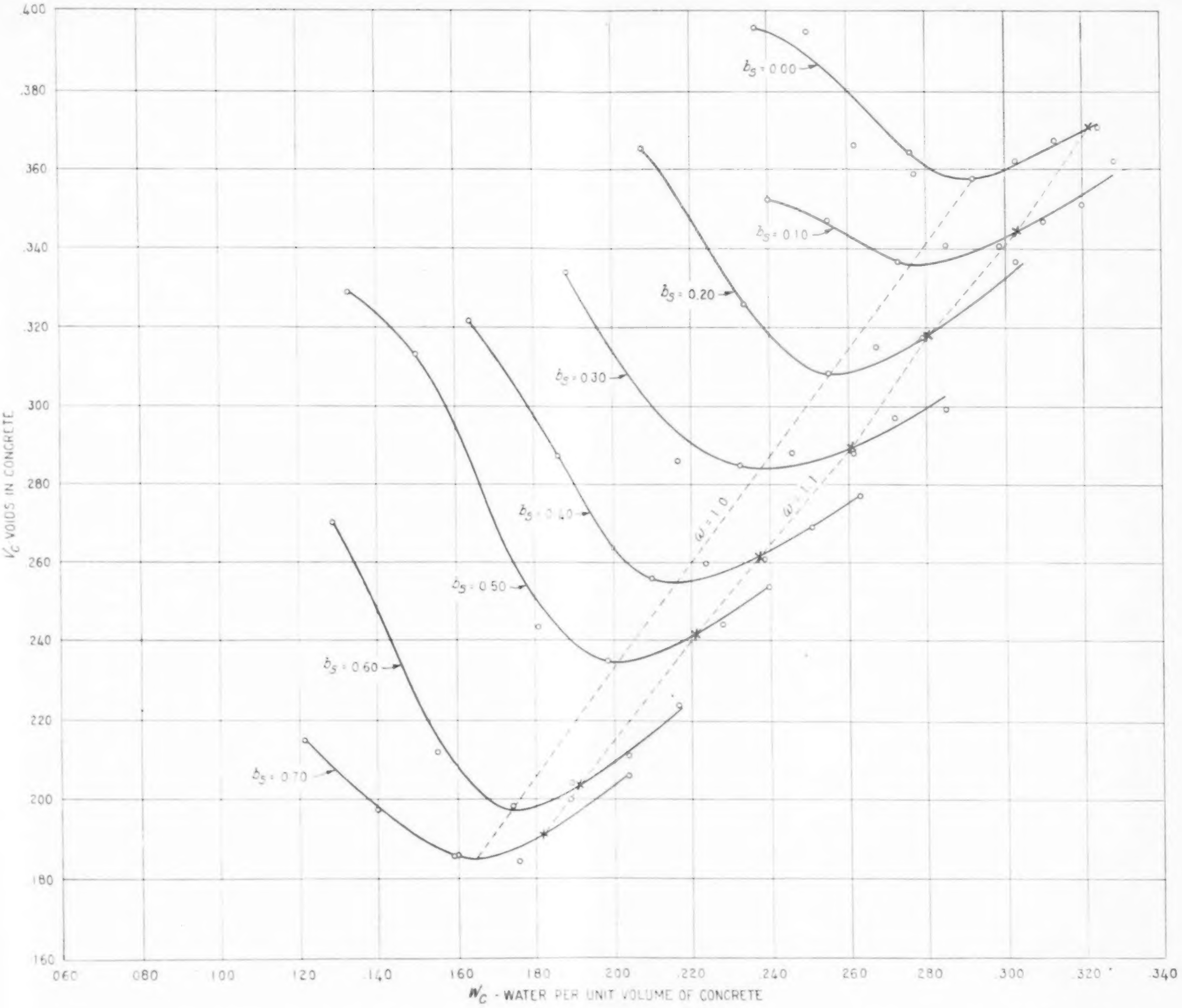


FIGURE 12.—CONCRETE-VOIDS CURVES FOR THIRD SERIES (VARYING VALUES OF b_s AND CONSTANT VALUE OF $\frac{a}{c}=2.576$).

ratio of compressive to flexural strength for all mixtures. This ratio varies from 3.33 to 7.70 with an average for all mixtures of 5.68.

The amount of water required to give maximum density to a particular mortar is not the same as that required to give maximum density to the concrete when coarse aggregate is added to this mortar. Additional water is required in the concrete by the coarse aggregate. Table 13 has been prepared from the concrete-voids curves for series 1 and 2 to show this relation. The last column shows the amount of water (in addition to that required for the mortar) in gallons per cubic foot of solid volume of coarse aggregate required to give maximum density to the concrete. The values are fairly consistent for all values of b_s for each of the two types of coarse aggregate used. The variations in the values are, no doubt, due to irregularities in the curves from which they were computed. These data indicate the necessity for making density determinations on the concrete mixture rather than on the mortar in the concrete.

CONCLUSIONS

The results of these tests corroborate general knowledge concerning the behavior of concrete mixtures. They shed new light and help to rationalize the complex relations existing in such mixtures. The following conclusions are based on these results:

1. For the range of water contents equal to or greater than basic, density determinations and the concrete voids curves resulting from them offer a definite basis for determining, for a given combination of particular materials:

The amount of water required to give maximum density and maximum strength. Expressing amounts of water in terms of this basic water content establishes a definite unit of measurement for designating the water required for any degree of workability.

The total voids for each relative water content. These data are necessary to accurately compute the solid volume of each ingredient required to produce a unit volume of concrete and the resulting water-cement ratio.

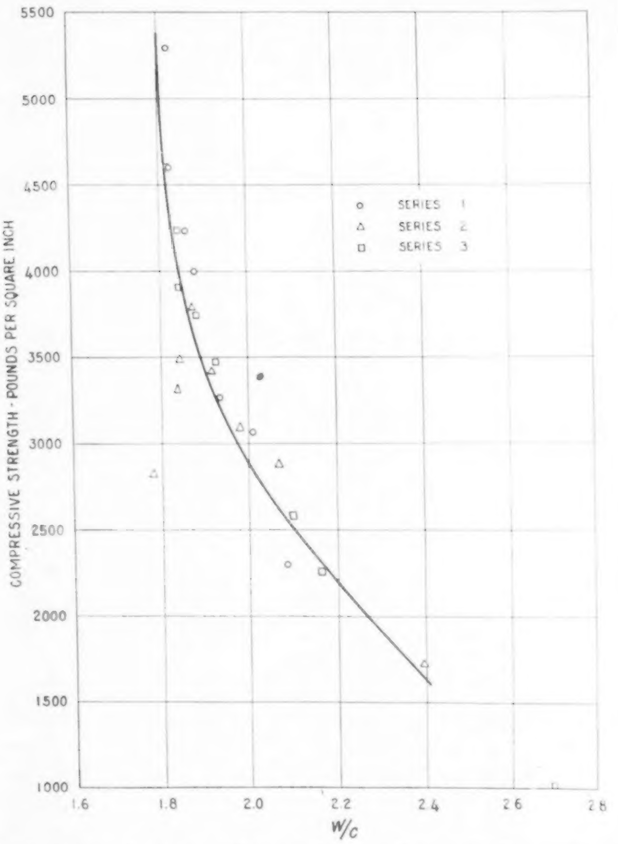


FIGURE 13.—EFFECT OF WATER-CEMENT RATIO ON COMPRESSIVE STRENGTH.

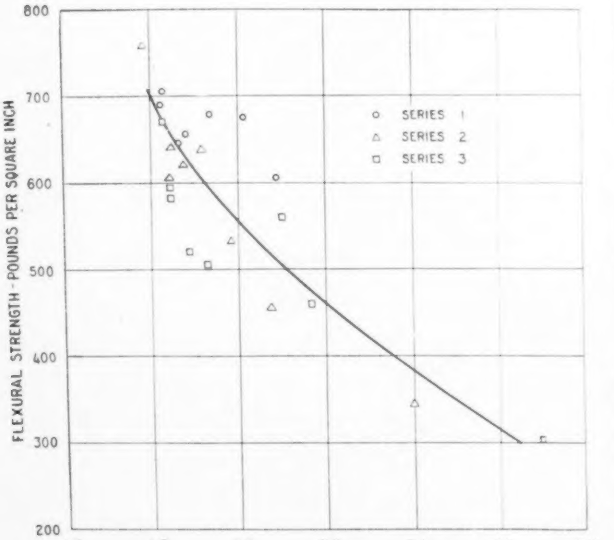


FIGURE 14.—EFFECT OF WATER-CEMENT RATIO ON FLEXURAL STRENGTH.

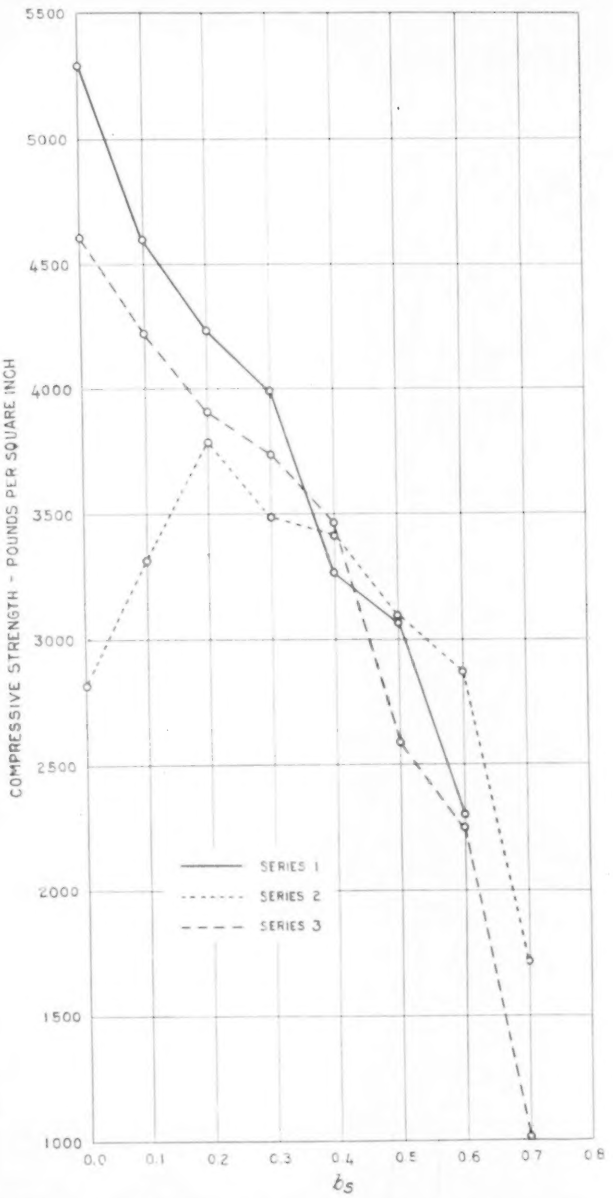


FIGURE 15.—EFFECT OF VARIATION IN COARSE AGGREGATE CONTENT ON COMPRESSIVE STRENGTH.

The effect of different kinds of ingredients on the amount of water required for maximum density and for different degrees of workability.

2. The density of the concrete should be determined rather than that of the mortar.

3. The amount of water required to give maximum density or to give a particular degree of workability may be different for every different combination of materials. To specify a fixed amount of water per unit volume of cement or concrete regardless of the proportions and characteristics of the ingredients is not sound.

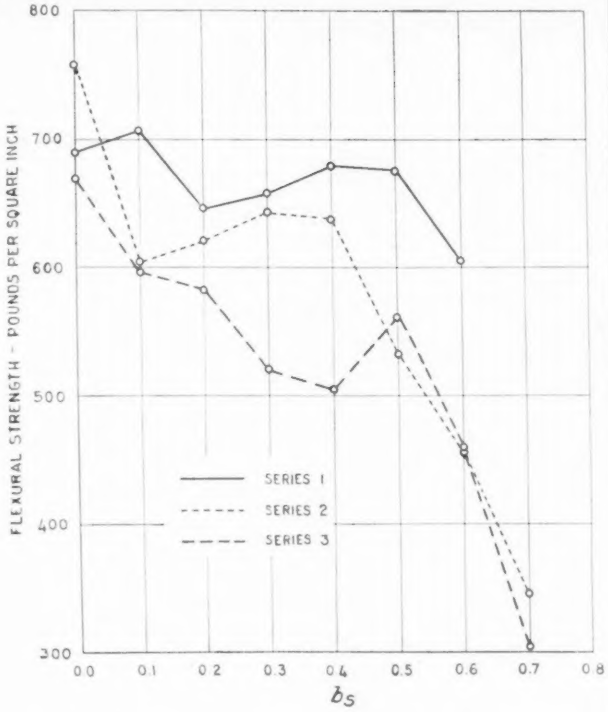


Figure 16.—Effect of Variation in Coarse Aggregate Content on Flexural Strength.

4. The strengths of different concrete mixtures composed of different kinds of materials apparently bear no relationship to their respective densities. The strength of a particular concrete mixture, however, can be expected to vary directly with its density, when the water content is equal to or greater than basic.

5. The symbols $\frac{a}{c}$ and b_s offer a definite basis for designating proportions. With these designations the proportions of the cement and aggregates remain constant, and do not change with changes in the relative water content, as would be the case were the proportions of these ingredients expressed as the ratios of their respective volumes to a unit volume of concrete. The method used is particularly convenient in designating the basic proportions of cement and aggregates to which increments of water are added in making density determinations for the concrete-voids curves.

6. The strength of concrete varies directly with the water-cement ratio.

7. The slump of a concrete mixture depends largely on its relative water content. For the same relative water content and the same kinds of ingredients, the slump will be about the same regardless of the proportions of cement, fine and coarse aggregate used in the mixture.

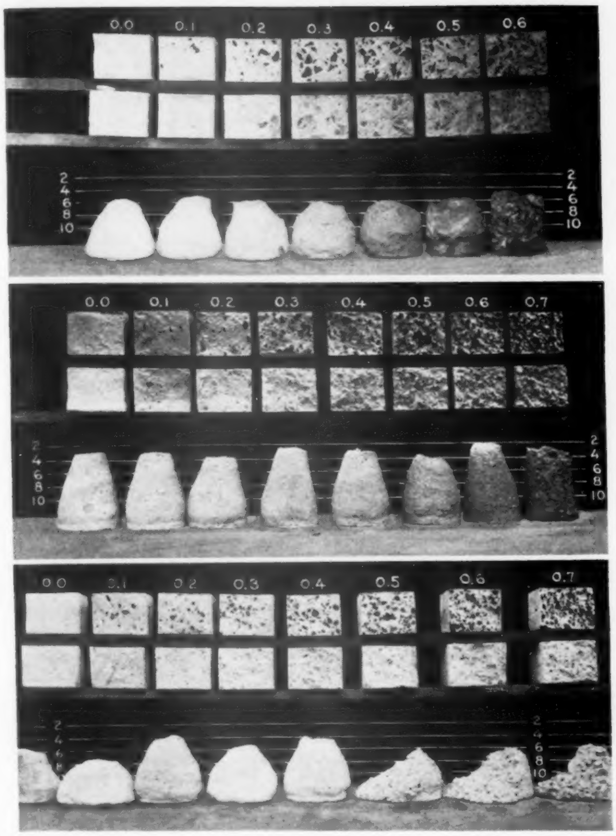


Figure 17.—Slump Test Specimens and Corresponding Beam Breaks for Test Series 1, 2, and 3 in the Order Named from Top to Bottom. Values of b_s are Shown Above Beam Specimens. Coarse Aggregate has been Painted on Upper Beam Break in Each Case.

8. A definite relationship evidently exists between the basic and relative water contents and the values of b_s for any particular value of $\frac{a}{c}$.

The results in the first group of tests indicate that a relation exists between the basic water content and the values of $\frac{a}{c}$ for any particular value of b_s. The range in the values of $\frac{a}{c}$ in this test, however, was not great, and the resulting values of W_c and V_c for each value of $\frac{a}{c}$ for this water content were rather close together. The direction that this relation will take, that is, whether the values of W_c and V_c will increase or decrease as the value of $\frac{a}{c}$ increases can be expected to be regulated by the characteristics of the sand and cement used, and by the particular range in the values of $\frac{a}{c}$ considered.

MECHANICAL ANALYSIS OF PORTLAND CEMENT BY THE HYDROMETER METHOD

BY THE DIVISION OF TESTS, UNITED STATES BUREAU OF PUBLIC ROADS

Reported by E. A. Willis, Assistant Highway Engineer, and C. M. Johnston, Junior Civil Engineer

THE hydrometer method of making a mechanical analysis of soils as described in the report "Procedures for Testing Soils for the Determination of the Subgrade Soil Constants", PUBLIC ROADS, volume 12, no. 8, October 1931, is adaptable, with few modifications, to the analysis of any fine-grained material. The chief advantages of the method are the ease and rapidity with which the analysis may be made, the flexibility of the procedure in respect to the number of grain sizes for which percentages may be determined and the suitability of the test for analyzing materials consisting of very small particles.

METHOD BASED ON STOKES' LAW

The previous article described a general method of analysis of fine-grained materials by the use of a hydrometer. A known weight of material is dispersed in a known amount of a suitable fluid. Settlement of particles takes place according to a physical law (Stokes' law), the larger particles settling most rapidly. Measurements of specific gravity are made with a hydrometer at various intervals of time. The specific gravity at any instant may be used to calculate the percentage of material remaining in suspension at that instant. A formula based on Stokes' law may be used to calculate the diameter of the largest particle in suspension at the time of measurement. Since it is approximately true that all larger particles have settled out of the liquid, the percentage of particles larger than the maximum size just referred to is easily determined.

The inherent errors of the method are described by R. C. Thoreen in an article entitled "Comments on the Hydrometer Method of Analysis", PUBLIC ROADS, volume 14, no. 6, August 1933. This report also describes a specially designed paddle and cup which are an improvement over those originally used.

This report describes in detail the procedure used in the mechanical analysis of portland cement. Since particles large enough to be retained on a 200-mesh sieve settle out of a liquid such as kerosene very rapidly, it was necessary to determine the percentage of larger particles by the ordinary screen analysis.

A series of sieves of square-mesh wire cloth, conforming to the standard specifications for sieves for testing purposes of the American Society for Testing Materials Serial Designation E–11, are used. The sieve numbers with their openings in millimeters are, resepctively: No. 10, 2.00 mm; no. 20, 0.84 mm; no. 40, 0.42 mm; no. 60, 0.25 mm; no. 140, 0.105 mm; and no. 200, 0.074 mm. A 50-gram sample of dried cement was used in the sieve analysis. Results of an analysis are shown in table 1.

The formulas necessary to compute the percentage of material in suspension in a liquid when the density is known and for computing the maximum diameter of particle in suspension are given below. The derivation of these formulas is discussed in the reports mentioned above.

TABLE 1.—*Results of sieve analysis of a 50-gram sample of cement*

Fraction				Total passing	
Passing sieve no. —	Retained sieve no. —	Weight	Amount	Amount	Diameter largest particle
		Grams	*Percent*	*Percent*	*Mm.*
10	20	0.000	0.0	100.0	0.840
20	40	0.000	0.0	100.0	0.420
40	60	0.000	0.0	100.0	0.250
60	140	0.150	0.3	99.7	0.105
140	200	1.850	3.7	96.0	0.074

For a 50-gram sample of cement dispersed in enough liquid to make 1,000 cubic centimeters of mixture,

$$D=\frac{G_k\left(1{,}000-\frac{\frac{50P}{100}}{G}\right)+\frac{50P}{100}}{1{,}000} \qquad (1)$$

in which D = density of the mixture of cement and kerosene,

G_k = specific gravity of the kerosene at the temperature at which D was obtained,

G = specific gravity of cement,

and P = percentage of dispersed cement in suspension.

Solving equation (1) for P,

$$P=2{,}000\ G\left(\frac{D-G_k}{G-G_k}\right) \qquad (2)$$

$$d=\sqrt{\frac{30nL}{980(G-G_k)T}}=\sqrt{\frac{.0306nL}{(G-G_k)T}} \qquad (3)$$

In this equation

d = maximum grain diameter in millimeters.

n = coefficient of viscosity of the suspending medium in poises. Varies with change in temperature of the suspending medium.

L = distance in centimeters through which particles settle in a given period of time.

T = time in minutes of sedimentation.

DETAILS OF TEST PROCEDURE DESCRIBED

A density type hydrometer is most satisfactory for the determination of the percentage of particles in suspension. In the investigations forming the basis of this report two hydrometers were used, since no single hydrometer covering the necessary range was available. The hydrometer should read from a minimum corresponding to the density of the kerosene used, to a maximum corresponding to the density of a suspension of 50 grams of cement per liter. For ordinary conditions a hydrometer having a range of 0.75 to 0.85 will be adequate.

A dispersing agent must be used in any mixture of cement with kerosene. Several dispersing agents in varying amounts were tried before it was found that 60 drops of oleic acid to the liter of kerosene was satisfactory. The oleic acid and kerosene should be mixed before the cement is added. It is important that the suspending medium be free of water and that the cement be thoroughly dry at the time of dispersion if flocculation is to be prevented.

The dispersion procedure is to fill the mixer cup to within 3 inches of the top with kerosene, add 60 drops of oleic acid, and mix for 1 minute. Remove cup, add 50 grams of oven-dried cement and add enough kerosene to bring the level to within 2 inches of the top, then stir in milk-shake machine for 15 minutes.

After dispersion, the mixture is transferred to a glass graduate and the dregs in the cup are washed into the graduate with more kerosene having the same constants and temperature as those used initially. Additional kerosene, having the same temperature as the constant temperature bath, is added until the mixture attains a volume of 1,000 cubic centimeters. The graduate containing the cement in suspension is then placed in the constant temperature bath. The liquid is stirred frequently with a glass rod to prevent settlement of the particles until the liquid attains the temperature of the bath. Then the graduate is removed and its contents thoroughly shaken for 1 minute. The palm of one hand is placed over the mouth of the graduate as a stopper and the graduate is given a slow end-for-end motion. At the conclusion of this shaking, the time is recorded, the graduate is placed in the bath and readings are taken on both the hydrometer and a thermometer in the liquid at the end of the following intervals in minutes: 1, 2, 5, 15, 30, 60, 250, and 1,440.

The hydrometer is always read at the top of the meniscus formed around its stem.

After the 5-minute reading is recorded, the hydrometer is very carefully removed from the liquid in such a manner as to cause no disturbance in it, is wiped clean and immersed in another graduate containing pure kerosene which is kept in the constant temperature bath. One minute before the time for another reading it is slowly and carefully replaced in the liquid being tested. This operation is performed to prevent cement particles from settling on the hydrometer and also to prevent the hydrometer from reducing the horizontal sectional area of the liquid through which the cement particles settle. The reading should not be taken until the hydrometer has come to rest.

Solution of the formulas requires information as to the specific gravity of the kerosene at the temperatures at which readings were taken, the coefficient of viscosity of the kerosene at the same temperatures, values of L for particle settlement, and the specific gravity of the cement. Specific gravity tests should be run on the kerosene at various temperatures and a curve plotted as shown in figure 1. Values corresponding to any temperatures can be taken from the chart. Similarly a chart for the viscosity-temperature relation is prepared, as shown in figure 2. Values for the viscosity coefficient were determined by means of an Engler viscosimeter using the formula suggested by the United States Bureau of Standards.[1]

[1] See "The Redwood Viscosimeter", by Winslow H. Herschel, U.S. Bureau of Standards Technological Paper no. 210, p. 243.

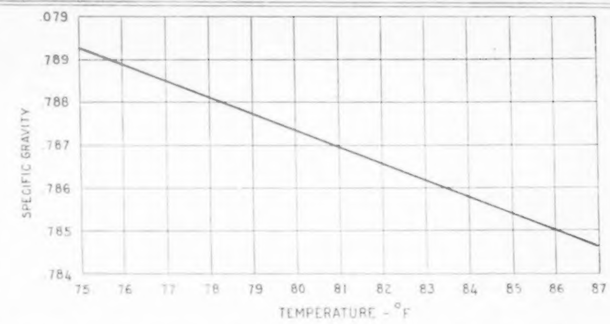


FIGURE 1.—SPECIFIC GRAVITY OF KEROSENE USED AT VARIOUS TEMPERATURES.

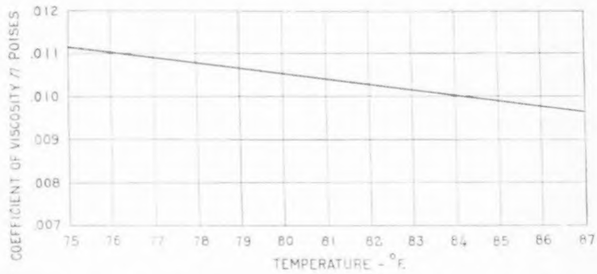


FIGURE 2.—VISCOSITY OF KEROSENE USED AT VARIOUS TEMPERATURES.

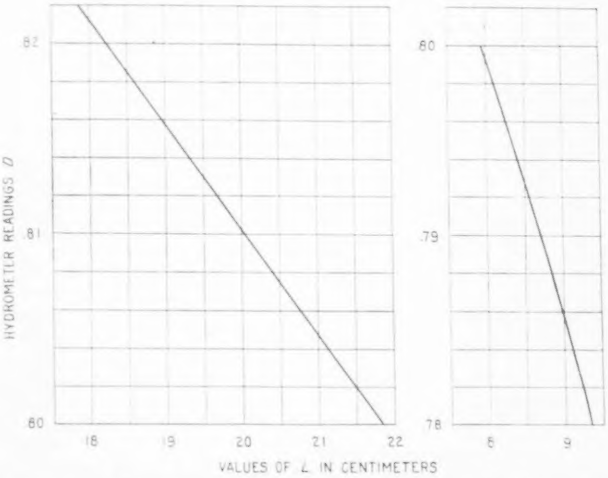


FIGURE 3.—VALUES OF L CORRESPONDING TO HYDROMETER READINGS FOR EACH HYDROMETER USED.

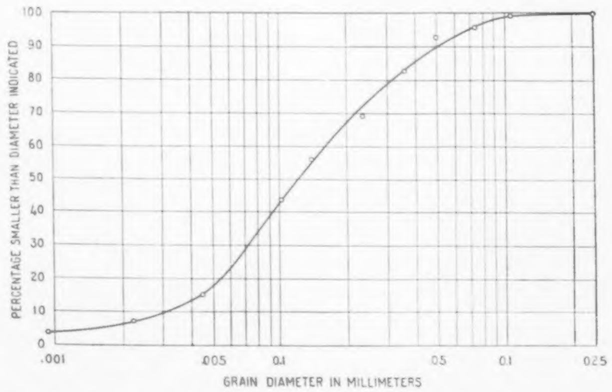


FIGURE 4.—GRAIN SIZE ACCUMULATION CURVE BASED ON DATA OF TABLES 1 AND 2.

Values of L, the distance through which the particles fall, were assumed to be the distance from the surface of the liquid to the center of volume of the hydrometer. Figure 3 shows such values for each hydrometer for various readings.

The specific gravity of the cement may be determined by the usual pycnometer method.

Table 2 shows the results of a series of hydrometer readings and the computations based on them.

As an example of the use of the formulas assume that it is desired to find the percentage, P, of cement in suspension after 2 minutes.

$$G=3.065, \text{ and } \frac{D-G_k}{G-G_k}=0.0136 \text{ when } T=2$$

$$P=2{,}000\times 3.065\times 0.0136=83.42 \text{ percent.}$$

Assume that it is desired to find the diameter of the largest particle in suspension after a 30-minute period of sedimentation. According to table 1, after a 30-minute period, the temperature was 77° F. Consequently, $G_k=0.7885$ and $n=0.01088$ poise. Since the hydrometer reading at this time was 0.8050 the distance L (fig. 3) equals 20.96 cm.

Solving equation 3 for d we obtain,

$$d=\sqrt{\frac{0.0306\times 0.01088\times 20.96}{2.2765\times 30}}$$

$$d=0.0101 \text{ mm.}$$

TABLE 2.—*Tabulation of observations and computations*

[Sample No. 11,724. Specific gravity = G = 3.065]

T	°F	D	G_k	D-G_k	G-G_k	$\frac{D-G_k}{G-G_k}$	n	L	P	d
Min.					$G=3.065$		*Poises*	*Cm.*	*Pct.*	*mm*
1	82	0.8210	0.7866	0.0344	2.2784	0.0151	0.01025	18.06	93	0.0499
2	81	.8180	.7870	.0310	2.2780	.0136	.01038	18.60	83	.0360
5	80	.8130	.7874	.0256	2.2776	.0112	.01050	19.51	69	.0235
15	78	.8090	.7881	.0209	2.2769	.0092	.01075	20.24	56	.0139
30	77	.8050	.7885	.0165	2.2765	.0072	.01088	20.96	44	.0101
60	77	.7940	.7885	.0055	2.2765	.0024	.01088	[1] 8.42	15	.00453
250	77	.7910	.7885	.0025	2.2765	.0011	.01088	8.64	7	.00225
1,440	77	,7895	.7885	.0010	2.2765	.0004	.01088	8.72	3	.00094

[1] The sudden change in values of L is due to the use of another hydrometer at this point.

The data in the last two columns of table 2 may be used to plot a grain-diameter accumulation curve as shown in figure 4 with the exception of the portion of the curve for diameters of over 0.05 millimeter. This portion of the curve is derived from the data of table 1. This curve is plotted on semilogarithmic paper.

OBSERVATIONS ON BULLDOZERS AND LARGE SCRAPERS IN GRADING WORK

BY THE DIVISION OF MANAGEMENT, UNITED STATES BUREAU OF PUBLIC ROADS

Reported by ANDREW P. ANDERSON, Highway Engineer

THE use of large tractor-powered bulldozers as actual excavating units and the use of large-capacity scrapers are comparatively recent innovations in highway grading. From time to time, this type of equipment has been found in use on jobs on which production studies were being conducted by the Bureau of Public Roads and the data thus accumulated will be summarized and reviewed briefly.

The bulldozer has long been standard equipment on the dump or fill, but its use in the cut as a combined excavating and hauling unit has, until recently, been very limited. All available data, however, indicate that the bulldozer and the modified type frequently known as the "trail builder" are well adapted to moving common excavation where the hauls are comparatively short and down rather steep grades and the materials are, or can be made, loose enough to permit the rapid accumulation of a load. If the material is at all hard or solid, it should be loosened with a rooter or a scarifier, or by blasting. The bulldozer is entirely satisfactory only where the ground is loose enough to permit a load to be picked up within a length of 25 to 40 feet with the tractor moving at a speed of 2.0 to 2.5 feet per second. If the material is too hard or tight to permit a full load to be picked up in from 10 to 20 seconds, it should be loosened with a rooter or by scarifying or by blasting.

BULLDOZERS USED IN CONJUNCTION WITH POWER SHOVEL

The tractor-powered bulldozer has thus far found its widest use as an excavating unit in conjunction with the power shovel when operating in rather rough, broken country with a deep mantle of soil or deeply weathered and decomposed rocks and shales. The bulldozer has certain characteristics which appear to limit its profitable operation as an excavating implement to jobs having these general features. It is most effective in moving material down steep slopes. As the grade decreases the efficiency decreases very rapidly, and on an ascending grade the efficiency of transportation is very low.

Proper material is essential. The material must be naturally loose or at least sufficiently friable to permit rapid and direct accumulation after loosening. Hard rocks and very hard shales can rarely be shattered sufficiently for movement with a bulldozer.

A relatively short haul is the third requirement. The tendency of the materials to spill around the ends of the bulldozer blade usually makes long movements unprofitable. Unless the grade is very steep a large load at the start will soon dwindle to a small one. Where a large yardage is moved along one path a trough or trench is formed by spillage around the ends of the blade and soon becomes sufficient to reduce further spillage. This advantage of path movement on long hauls should be utilized as much as possible. Sometimes the spillage around the ends of the bulldozer blade can be reduced by working two bulldozers abreast with their blades only a few inches apart. Observations on a job where this was tried indicated that the yardage moved per trip by the two tractors was increased nearly 20 percent over that moved when working independently.

The bulldozer is particularly useful in conjunction with the power shovel. On steep ground the pioneer road work necessary for the shovel to reach the first

Cut Illustrated on Cover Page at an Advanced Stage of Construction.

The Largest Loads are Moved on Steep Grades.

lift of a deep cut can frequently be greatly reduced and sometimes entirely eliminated by having the bulldozer build up both an approach for the shovel and a hauling road for the trucks or wagons. Often a cut which would normally be made in two or three lifts may be reduced in this way by one lift and better hauling roads provided because of the adaptability of the bulldozer to the conditions. With the bulldozer this can generally be done with the movement of only pay materials, whereas the older method frequently requires the movement of considerable quantities of nonpay materials in the construction of approach roads in zigzags up the steep slopes.

The bulldozer has been found effective in sidehill work. Work is usually begun along the upper line of slope stakes and the material moved ahead and to the side as the conditions may require. So long as the material is loose or can be loosened and the haul distance is short enough to maintain a rather steep grade along which to move the material, good production rates can be maintained.

The best operating speed at which to haul the loads is still largely a matter of opinion. The general practice is to work at about the maximum speed possible without obviously straining the power unit. This practice may be entirely correct for many or possibly most cases. It was noted during recent job studies that in moving loose, noncohesive material down steep grades the amount of material which would push or flow in front of the blade was much larger at a speed of 2 feet per second or less than for a speed of 3.5 feet per second. There appears to be some optimum speed which will yield the greatest production, at least when moving loose, noncohesive materials down steep grades. However, no definite data are available as to what this most productive speed is or how it may vary with different materials and on different slopes.

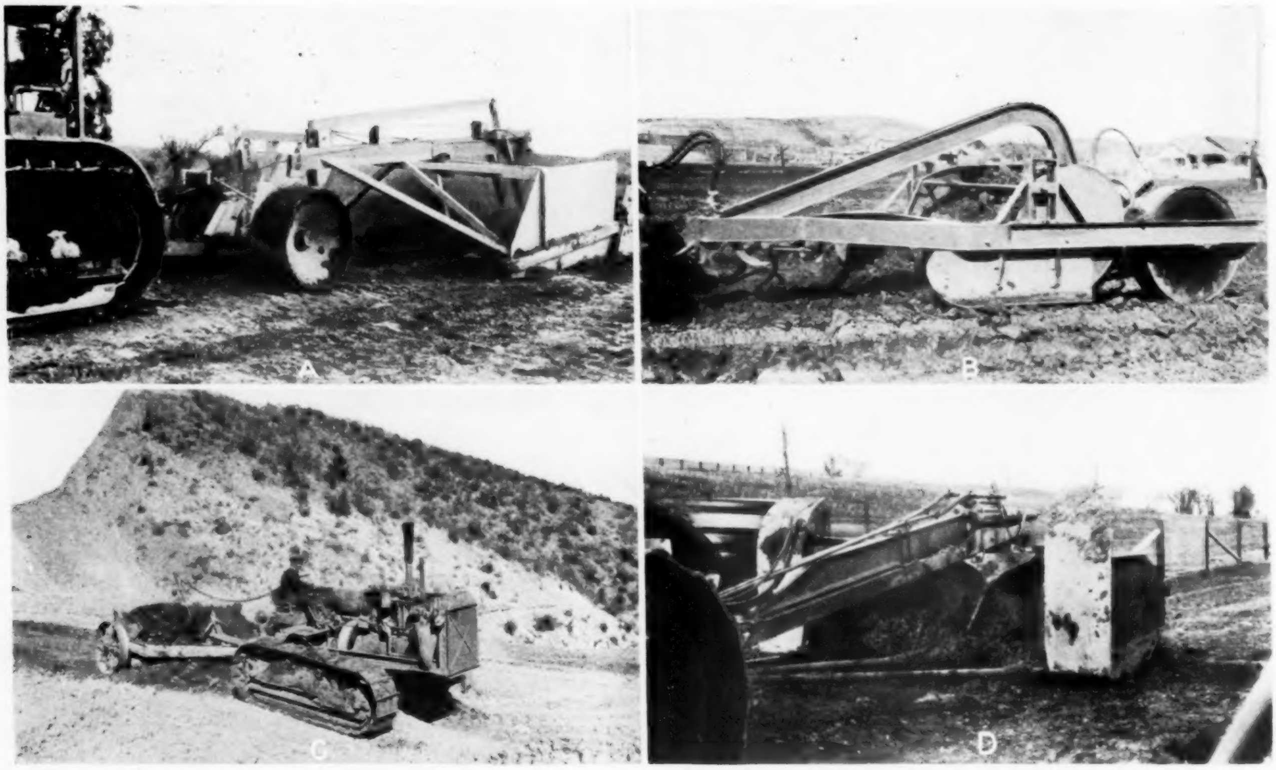
Opening a cut with the bulldozer in ground as described above is comparatively simple, although on very steep ground considerable skill and ingenuity are required in maneuvering the bulldozer in its climb to the very top of the cut. Once this point has been reached the bulldozer begins to dig along the highest point of the upper slope line. The excavated material is pushed ahead toward the fill. If the ground slope is steeper than the tractor can readily climb in reverse, the material is simply pushed clear of the immediate excavation and allowed to accumulate along the line of the hauling road until a runway is provided with flat enough grade to permit the bulldozer to return readily in reverse after delivery of its loads to the fill. If the ground slope is already flat enough for the tractor to return fairly easily, every load is carried to the fill. In both cases the slope of the hauling road for the bulldozer is kept as steep as possible because, within limits, the steeper the grade the larger the load which can be carried to the fill.

As the work progresses the runway is widened to finally include the full width of the cut. In a wide cut three or four bulldozers can sometimes be operated without interference, and even more if the haul is in both directions. If the material becomes too hard for easy loading, a heavy scarifier or rooter drawn by a powerful tractor may be used to loosen it. If the ground becomes still harder, blasting should be resorted to. The harder rocks and shale, however, can seldom be reduced sufficiently to make the use of the bulldozer profitable. When rock or ground of this nature is reached further work is left to the power shovel.

The steeper the grade the larger the load which can be carried to the fill and the longer the haul on which the bulldozer can be used profitably. The only limit to the grade is the ability of the tractor to climb on the return. A large crawler tractor in good condition and equipped with a 10-foot standard bulldozer has been observed to climb a grade as steep as 50 percent.

Field observations indicate that the average load which can be carried from cut to fill under ordinary field conditions varies with the length and shape of the blade, the grade along which the load is moved, and the character of the material. The observations are confirmed to some extent by the data of table 1. During recent studies of the use of four bulldozers in moving considerable yardages it was found that loads frequently fluctuated as much as 100 percent. For a certain bulldozer the smallest loads would be about 2 cubic yards, and the largest loads would be about 4 cubic yards.

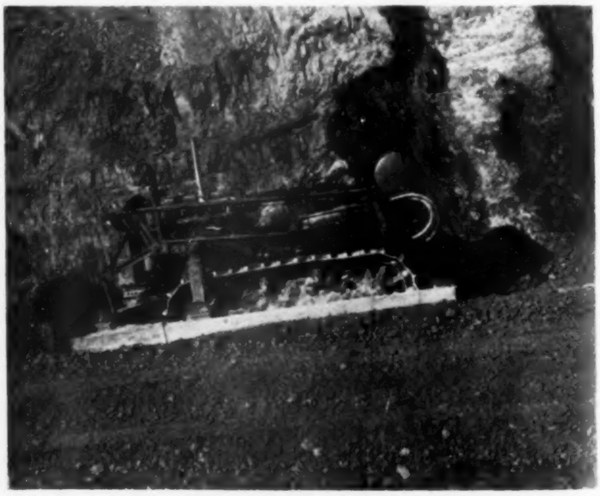
Recent improvements in control which permit independent vertical movement of either end of the bulldozer and also lateral movement have considerably improved the utility. It is easier to keep the entire cut in proper condition for easy operation, and to shape



A, Scraper Without Front Closure in Loading Position. Load is Dumped by use of Cable Which Pulls Back Plate Forward. B, Scraper with Full Load and Pushing Earth Before It. C, Scraper Arriving at Dump with a Full Load. D, A Type of Scraper which Dumps by Overturning on Front Shoes.

Table 1.—*Operation characteristics of tractor-powered bulldozers*

	Bulldozer no.			
	1	2	3	4
Number of trips timed	3,731	511	800	560
Cubic yards placed in fill	11,741	1,655	1,822	1,352
Production rate ... cubic yards per hour	68.4	57.0	35.2	44.1
Pay yardage per load ... cubic yards	3.15	3.24	2.28	2.41
Loading distance ... feet	30.0	40.0	28.0	39.0
Loading speed ... feet per second	2.4	2.4	1.4	2.7
Haul distance ... feet	168	216	309	232
Hauling speed ... feet per second	3.7	3.2	3.2	3.1
Return distance ... feet	200	260	340	275
Return speed ... feet per second	2.3	2.5	4.7	2.5
Average grade ... percent	−26	−17	−11	−20
Operating cycle:				
Load ... seconds	12.6	16.6	20.6	14.3
Reverse or turn at dump ... do	1.9	2.0	2.6	2.5
Turn or shift at cut ... do	2.0	2.4	2.8	2.4
Minor time losses, percentage of working time	12.6	14.5	18.0	16.2
Size of blade ... feet	4 by 10	3 by 11.5	4 by 10	4 by 10
Rated horsepower of tractor	65	65	60	60



Material Loosened by Scarifying and Moved with a Bulldozer.

the slopes at the proper angle. These features are particularly valuable in sidehill work.

LARGE TRACTOR-DRAWN SCRAPERS STUDIED

Large tractor-drawn scrapers have been studied on a few grading jobs having large quantities of short-haul common excavation. These scrapers ranged in rated capacity from 3 to 8 cubic yards of loose material and were of six different makes. This number of different makes indicates that this type of equipment is far from standardized. However, those observed may be divided into two distinct classes: Those which carry the load pan or scoop clear of the road, and those which drag the load pan or cutting blade so as to transport a part or all of the load by pushing it ahead of the pan or cutting blade.

Some of those which lift the pan have definite provisions for preventing or reducing spillage while the load is being hauled to the dump. These provisions vary from substantial self-closing gates to simply tilting the load pan to such an angle that the tendency for the material to spill out is greatly reduced. In the other class, the pan is raised very little for the haul and spillage is prevented or at least neutralized by accumulating and dragging material in front of the pan.

Loading a Large Scraper.

End-Gate Type of Scraper in Hauling Position, Showing Gate Closed and Body Clear of Ground in Hauling Position.

Table 2.—*Operating characteristics of large scrapers*

	Scraper no.			
	1	2	3	4
Rated capacity ... cubic yards	3	6	8	4
Condition of equipment	Good	Very good	Very good	Very good
Number of round trips timed	212	269	132	145
Loading distance ... feet	75	116	144	80
Loading speed ... feet per second	2.3	1.8	2.0	2.1
Hauling distance ... feet	180	327	290	210
Hauling speed ... feet per second	2.9	3.5	2.8	3.0
Return distance ... feet	254	405	449	280
Return speed ... feet per second	3.2	3.8	3.8	3.7
Dumping time ... seconds	10.4	-----	-----	-----
Turning time ... do	18.0	22.0	20.0	24.0
Size of load carried to dump, percentage of apparent full load	95.0	75.0	50.0	80.0
Average pay yardage in percentage of rated load capacity	57.0	45.0	35.0	54.0

	Scraper no.			
	5	6	7	8
Rated capacity ... cubic yards	5	4	4	5
Condition of equipment	Very good	Fair	Good	Fair
Number of round trips timed	54	56	3,200	963
Loading distance ... feet	86	92	100	38
Loading speed ... feet per second	2.0	1.8	2.0	2.3
Hauling distance ... feet	372	1,400	300	237
Hauling speed ... feet per second	3.2	3.0	2.5	3.3
Return distance ... feet	450	1,450	400	275
Return speed ... feet per second	3.8	4.7	5.5	2.7
Dumping time ... seconds	46.0	34.0	11.0	10.4
Turning time ... do	27.0	22.0	20.0	-----
Size of load carried to dump, percentage of apparent full load	61.0	75.0	90.0	-----
Average pay yardage in percentage of rated load capacity	37.0	45.0	53.0	44.0

Scarifying Material for Easy Loading by Scrapers or Bulldozers.

Adjusting the pan so as to drag material produced a considerable effect on the hauling speed. When the scraper was hauled with the load pan clear of the ground the hauling speed was generally 30 to 50 percent higher than when the pan dragged sufficiently to retain a full load. The effect of reduced speed, however, seemed fully compensated by the increased load. With the pan hoisted entirely clear of the roadway, the loss from spillage on steep or rough down grades was as much as one half of the original load when the soil was dry and noncohesive. Considerable difficulty was sometimes experienced in dumping the gate type of scraper when working in sticky or plastic materials.

Results of observations on four jobs using six different types of scrapers are shown in table 2. Scrapers 1, 2, 3, 4, and 5 were all on one job and operated under fairly similar conditions. Job 7 was observed only in the winter when the materials were wet, sticky, and difficult to handle. Scrapers and 1 and 7 and 5 and 6 were of the same make and type but were observed on different jobs and under different conditions.

CURRENT STATUS OF U.S. PUBLIC WORKS ROAD CONSTRUCTION AS PROVIDED IN TITLE II, SECTION 204 OF THE NATIONAL INDUSTRIAL RECOVERY ACT

CLASS I—PROJECTS ON THE FEDERAL-AID HIGHWAY SYSTEM OUTSIDE OF MUNICIPALITIES

AS OF APRIL 30, 1934

STATE	PUBLIC WORKS FUNDS ASSIGNED FOR CLASS I PROJECTS ON THE FEDERAL AID HIGHWAY SYSTEM	COMPLETED				UNDER CONSTRUCTION					APPROVED FOR CONSTRUCTION		BALANCE OF PUBLIC WORKS FUNDS AVAILABLE FOR NEW CLASS I PROJECTS
		Total cost	Public works funds	Regular Federal aid	Mileage	Estimated total cost	Public works funds allotted	Regular Federal aid allotted	Percentage completed	Mileage	Public works funds allotted	Mileage	
Alabama	$4,185,067.00	$133,076.15	$73,641.88	$59,434.27	5.0	$5,154,764.40	$2,850,690.43	$2,304,073.97	47.2	287.4	$366,087.29	25.6	$894,647.40
Arizona	3,804,731.00	1,178,418.45	1,178,418.45		79.5	2,763,906.32	2,204,970.38		32.5	191.5	191,326.54	5.8	230,015.63
Arkansas	3,374,167.00	118,950.68	84,285.68	34,665.00	6.0	2,401,810.33	1,959,044.89	442,765.44	41.1	111.8	547,468.32	50.0	783,368.11
California	7,803,677.00	1,603,685.04	1,363,993.73		60.1	7,711,638.66	5,755,125.65		36.3	212.9	642,341.58	29.1	42,216.04
Colorado	3,437,265.00	1,055,865.36	1,055,865.36		76.2	2,019,670.24	2,009,089.89		35.1	61.0	231,925.98	7.1	140,383.77
Connecticut	1,404,213.00					1,540,038.02	1,364,259.08	175,778.94	12.4	30.7	36,199.68	.1	3,754.24
Delaware	909,544.00	133,532.30	133,532.30			760,029.30	760,029.30		31.8	17.4			15,982.40
Florida	2,615,917.00	531,031.10	375,168.86	155,862.24	17.6	2,603,100.11	1,973,078.14	629,411.87	54.7	91.4	111,884.12	7.0	155,785.88
Georgia	5,045,592.00	467,980.22	467,980.22		24.5	2,460,868.26	2,460,868.26		69.9	161.0	879,827.92	56.3	1,236,915.60
Idaho	2,166,858.00	453,733.29	450,147.98		52.4	1,448,016.23	1,436,689.50		41.9	106.0	72,674.31	15.4	207,346.21
Illinois	4,431,348.00					1,590,705.85	1,590,705.85		24.5	37.0	1,722,506.15	19.4	1,118,136.00
Indiana	4,717,786.00					2,271,340.43	2,271,340.43		33.3	74.7	1,840,720.20	45.2	605,725.37
Iowa	5,027,830.00	723,735.69	721,500.00		31.6	4,335,833.29	4,086,830.00		39.9	228.0	194,125.50	9.5	25,374.50
Kansas	5,044,802.00	713,689.65	713,689.65		131.2	4,291,580.19	4,127,302.66		54.5	261.2	202,628.05	5.2	1,181.64
Kentucky	3,608,332.00	148,867.77	144,997.64		12.1	2,666,046.69	2,666,046.69		32.1	201.9	510,800.52	30.1	286,487.15
Louisiana	2,914,295.00	60,721.48	60,721.48		1.9	2,660,910.57	2,194,259.57		30.2	65.9	497,709.81	10.5	201,604.14
Maine	1,617,560.00					1,167,849.93	1,132,282.98		41.5	35.5	385,700.18	8.8	99,576.84
Maryland	1,782,263.00					801,143.78	791,495.03		15.5	14.8	316,871.75	6.4	673,896.22
Massachusetts	1,101,716.00	153,936.88	83,952.64	69,984.24	4.2	1,235,131.88	919,472.24	315,659.64	32.0	33.6	12,521.88		85,769.24
Michigan	5,094,491.00	63,000.00	63,000.00		1.7	3,491,050.00	3,491,050.00		28.1	177.3	1,540,441.00	61.9	
Minnesota	5,115,153.00	1,701,597.69	1,701,597.69		381.5	1,880,412.23	1,880,412.23		33.7	257.0	814,722.62	95.8	718,420.46
Mississippi	3,489,337.00	155,273.60	85,400.49	69,873.11	6.6	3,744,584.87	2,023,552.54	1,682,400.39	31.5	199.7	574,040.62	45.1	806,343.35
Missouri	5,237,532.00	522,010.24	397,362.24		28.7	4,306,843.30	3,940,425.23	50,048.60	43.9	148.1	344,047.92	11.8	555,696.61
Montana	4,463,849.00	784,377.15	784,377.15		77.9	3,772,325.19	3,359,523.76	332,801.43	34.2	257.1	278,767.99	23.7	41,180.10
Nebraska	3,914,481.00	377,339.04	255,419.54		144.8	4,378,870.30	3,280,762.23	108,538.00	49.2	203.0	378,298.23	14.0	1.00
Nevada	2,909,387.00	553,682.77	553,682.77		82.5	2,078,604.14	2,078,604.14		32.1	170.2	260,637.03	7.4	16,463.06
New Hampshire	725,739.00					584,339.36	577,831.95		46.0	9.8	68,469.25	1.0	79,437.80
New Jersey	3,099,370.48	12,742.75	12,742.75		.2	2,725,372.69	2,570,451.68	139,466.42	10.7	34.6	16,272.89		499,903.16
New Mexico	2,896,467.00	1,370,897.67	1,370,897.67		165.5	1,586,318.70	1,449,959.22	102,921.33	17.7	111.7	44,621.19	1.8	30,988.92
New York	10,271,846.00	315,707.14	215,707.14	43,000.00	7.4	10,717,688.68	9,552,963.68	315,000.00	24.3	221.5	445,487.15	10.8	57,688.03
North Carolina	4,761,147.00	667,973.20	410,195.45	257,777.75	53.5	2,620,617.03	2,303,365.92	316,790.92	45.0	367.7	1,143,228.39	160.5	904,357.24
North Dakota	2,902,224.00	510,757.38	510,753.87		265.8	1,332,394.06	1,280,222.21	52,171.85	18.9	368.3	882,547.23	284.6	228,700.69
Ohio	7,277,758.00	415,362.41	413,768.57		9.7	6,908,623.00	6,614,390.00	51,410.00	35.1	173.6	202,600.00	8.4	46,999.43
Oklahoma	4,608,399.00	305,249.23	305,140.15		21.9	3,708,272.93	3,708,272.93		45.8	246.2	233,819.14	29.6	361,166.78
Oregon	3,053,448.00	630,587.33	518,376.33		50.2	2,468,032.27	2,312,693.07	58,505.67	37.3	126.9	179,484.99	6.0	42,893.61
Pennsylvania	6,691,194.00	15,425.22	15,425.22		.2	5,468,094.10	5,424,889.93		17.6	115.2	915,209.55	14.9	335,669.30
Rhode Island	999,354.00	18,144.13	18,144.13		.5	979,621.58	979,621.58		32.6	20.0			1,588.29
South Carolina	2,729,583.00	51,527.78	51,527.78		.9	1,962,686.24	1,959,956.62	2,729.62	46.4	184.4	367,445.24	35.7	350,653.36
South Dakota	3,005,739.00	702,954.32	683,612.93	19,341.39	120.3	1,457,393.87	1,367,255.45	90,138.22	30.9	240.5	588,556.54	87.2	366,314.08
Tennessee	4,246,309.00	335,262.04	249,789.43	85,472.61	11.5	3,582,358.40	3,091,813.63	490,544.77	38.3	135.9	654,994.21	38.4	249,711.73
Texas	12,122,012.00	1,605,722.44	1,204,742.39		321.9	9,029,593.61	8,146,344.52		36.8	608.7	1,194,113.68	93.3	1,576,811.41
Utah	2,374,205.00	973,028.84	971,166.45		110.2	1,193,094.86	1,165,183.77		35.5	83.1	69,948.52	1.5	167,906.26
Vermont	928,184.00	47,983.81	47,983.81		6.2	735,351.85	707,198.60		38.8	34.7	158,637.24	4.0	14,364.35
Virginia	3,708,379.00	412,940.60	395,367.62	17,572.98	16.5	2,614,973.41	2,504,313.45	110,659.96	30.6	76.2	732,555.06	53.7	76,142.87
Washington	3,057,934.00	334,913.47	334,229.63		17.5	2,305,188.36	2,301,831.54	3,356.82	39.0	78.0	418,666.27	11.4	3,206.56
West Virginia	2,013,405.00	194,881.82	194,881.82		6.4	1,613,052.72	1,607,052.72		42.3	63.7	131,760.68	2.2	79,709.78
Wisconsin	4,862,441.00	307,513.14	297,210.31	1,190.00	15.7	2,770,852.54	2,702,036.77	21,500.00	37.2	109.0	1,463,244.04	97.7	399,949.88
Wyoming	2,250,663.00	912,725.90	797,131.00	78,000.00	163.8	1,432,898.15	1,313,540.00	58,200.00	18.9	280.0	107,708.02	14.7	32,283.98
District of Columbia													
Hawaii	1,683,956.00	85,729.28	72,722.15	12,994.32	4.2	1,379,099.46	1,143,819.31	185,280.15	22.7	25.3	218,720.78	3.3	248,693.76
TOTALS	185,486,949.48	21,862,540.45	19,840,252.35	905,167.91	2,596.0	142,712,992.38	127,352,919.65	8,040,154.01	34.9	7,351.1	23,192,365.25	1,551.9	15,101,412.23

CURRENT STATUS OF U.S. PUBLIC WORKS ROAD CONSTRUCTION

AS PROVIDED IN TITLE II, SECTION 204 OF THE NATIONAL INDUSTRIAL RECOVERY ACT

CLASS II—PROJECTS ON EXTENSIONS OF THE FEDERAL-AID HIGHWAY SYSTEM
INTO AND THROUGH MUNICIPALITIES

AS OF APRIL 30,1934

STATE	PUBLIC WORKS FUNDS ASSIGNED FOR CLASS II PROJECTS IN MUNICIPALITIES	COMPLETED				UNDER CONSTRUCTION					APPROVED FOR CONSTRUCTION		BALANCE OF PUBLIC WORKS FUNDS AVAILABLE FOR NEW CLASS II PROJECTS
		Total cost	Public works funds	Regular Federal aid	Mileage	Estimated total cost	Public works funds allotted	Regular Federal aid allotted	Percentage completed	Mileage	Public works funds allotted	Mileage	
Alabama	$ 2,092,533	$ 94,891.56	$ 94,891.56		1.5	$ 513,265.88	$ 513,265.88		18.3	16.1	$ 668,475.73	19.4	$ 815,899.83
Arizona	781,794	22,538.90	22,538.90		.8	218,896.37	217,455.49		52.9	6.3	386,886.59	4.3	154,913.02
Arkansas	1,687,084	17,506.70	15,826.70	$ 1,680.00	.3	815,777.57	737,822.36	$ 77,955.21	46.6	23.1	743,738.90	13.1	189,696.04
California	3,901,839	624,384.83	561,419.81		9.1	2,347,828.51	2,107,471.21		19.4	29.2	972,565.01	11.1	260,382.97
Colorado	1,718,633	267,964.98	222,157.33		5.6	909,226.59	909,226.59		29.3	17.2	452,837.21	10.6	134,411.87
Connecticut	802,407	48,325.68	48,325.68		.5	677,318.83	676,491.74		29.0	9.2	68,293.81	.5	9,295.77
Delaware	454,772	75,309.50	75,309.50		.8	196,685.90	196,685.90		11.7	1.9	81,105.00	1.0	101,671.60
Florida	1,307,959	120,149.54	66,194.72	53,954.82	2.0	1,407,312.64	1,223,502.25	183,810.39	28.8	15.2	18,262.03	.2	
Georgia	2,724,620	168,636.21	168,636.21		7.1	761,533.73	761,533.73		31.6	26.5	479,128.55	16.1	1,315,321.51
Idaho	1,197,829	35,981.47	35,773.52		1.8	417,310.23	411,366.65		37.9	10.6	424,722.40	3.0	325,966.43
Illinois	6,877,199	58,782.38	58,782.38		.8	5,812,406.26	5,812,406.26		16.0	60.5	1,006,010.36	9.7	
Indiana	4,818,165	42,730.27	42,730.27		.8	390,182.76	390,182.76		2.3	9.9	3,003,164.55	56.1	1,382,087.42
Iowa	2,815,585	243,532.64	242,350.00		8.6	1,180,110.31	1,107,595.00		27.1	23.5	524,474.50	14.4	941,165.50
Kansas	2,522,401	114,205.11	114,205.11		5.4	2,382,465.43	2,230,057.18		43.7	28.9	177,763.60	2.6	375.11
Kentucky	2,029,687	13,307.85	13,307.85		.2	562,107.36	562,107.36		14.4	11.7	410,045.28	11.7	1,044,226.51
Louisiana	1,457,148	159,911.74	159,911.74		2.5	294,238.30	294,238.30		54.4	9.5	1,002,997.96	15.1	
Maine	909,878	78,429.27	78,305.71		1.4	415,559.35	415,559.35		36.6	9.9	339,937.36	5.2	76,075.58
Maryland	891,132					16,788.76	12,638.76		99.0	.6			878,493.24
Massachusetts	5,007,199	53,896.49	30,896.49	23,000.00	1.5	3,946,565.68	3,932,465.68	14,100.00	19.7	12.7	250,293.28	1.0	793,543.55
Michigan	4,457,679	180,700.00	180,700.00		2.3	2,428,266.00	2,426,116.00		10.8	29.8	598,975.00	7.2	1,251,888.00
Minnesota	3,410,102	587,385.43	587,385.43		38.5	1,061,746.24	1,061,746.24		32.8	33.3	575,083.10	17.6	1,187,887.23
Mississippi	1,744,669	103,306.43	99,556.17	3,750.26	2.9	379,382.30	370,673.06	8,709.24	8.1	15.9	319,297.77	11.3	955,142.00
Missouri	4,019,501	79,441.39	77,155.86		2.2	1,722,682.85	1,584,251.58		53.7	30.9	689,512.52	12.8	1,668,581.04
Montana	1,115,962	8,857.31	8,857.31		1.0	560,206.07	560,206.07		26.4	14.7	379,417.34	12.3	167,481.28
Nebraska	1,957,240	28,782.40	28,093.11		3.6	1,452,124.90	1,452,124.90		24.0	21.7	476,567.75	8.0	454.24
Nevada	500,051	50,304.27	50,304.27		1.2	45,973.80	45,973.80			1.3	331,880.89	5.7	71,892.04
New Hampshire	706,640					592,825.47	592,825.47		15.7	14.4	113,814.53	2.1	
New Jersey	3,190,118	99,752.39	99,752.39		2.1	2,605,324.28	2,551,191.28	30,000.00	26.6	18.6	123,082.10	.5	416,092.23
New Mexico	1,448,234	132,598.88	132,598.88		5.3	1,087,965.44	1,087,965.44		21.9	20.3	81,974.48	4.1	145,695.20
New York	8,449,487	123,574.54	123,193.24		2.1	7,356,177.60	6,907,745.00	39,000.00	21.1	56.9	725,252.70	3.0	693,296.06
North Carolina	2,380,573	136,289.35	136,289.35		7.3	708,428.99	706,793.70		25.6	29.6	474,703.51	20.0	1,062,786.44
North Dakota	1,451,112	2,153.29	2,153.29		1.0	231,430.79	204,421.06	27,009.73	18.6	11.7	522,161.67	18.9	722,375.98
Ohio	4,335,686	73,956.80	62,264.08		2.0	3,590,564.43	3,215,249.43		18.3	41.9	964,984.00	14.0	93,188.49
Oklahoma	2,304,200	36,756.66	36,740.13		2.5	1,506,053.88	1,506,053.88		24.0	28.6	514,514.25	12.6	246,891.74
Oregon	1,526,724	99,566.50	99,566.50		2.0	1,080,582.35	1,059,218.76	14,315.73	21.2	19.6	87,027.53	3.7	280,911.21
Pennsylvania	4,854,988	178,972.50	178,140.66		5.1	2,050,367.30	2,006,816.04		26.7	33.1	1,516,324.34	17.5	1,153,706.96
Rhode Island	499,677					351,090.02	351,090.02		12.0	5.3	66,224.98	1.1	82,362.00
South Carolina	1,364,791	37,322.12	37,322.12		2.0	427,299.38	426,894.37	405.01	31.6	20.9	302,359.13	10.8	598,215.38
South Dakota	1,502,870	148,279.48	148,279.48		7.0	286,290.13	286,290.13			9.3	670,760.85	21.0	397,539.54
Tennessee	2,123,155	89,510.69	89,510.69		2.5	949,476.28	949,476.28		30.8	12.7	320,432.68	5.8	763,735.35
Texas	6,061,006	422,531.62	383,362.80		22.1	2,963,557.58	2,809,482.00		30.9	62.0	1,328,910.87	24.6	1,539,250.33
Utah	771,826	402,641.81	391,682.07		9.0	194,944.70	193,186.32		68.3	5.9	60,000.00	1.8	126,957.61
Vermont	500,509	3,854.07	3,854.07		.7	385,151.18	375,663.48		18.1	10.2	120,991.45	3.7	
Virginia	1,854,189	184,013.92	174,362.04	9,651.88	6.5	1,302,512.21	1,105,439.73		16.3	13.1	557,167.32	7.8	17,219.91
Washington	1,877,571	286,522.39	275,125.01		6.1	1,597,697.40	1,594,992.67		27.7	25.7	7,453.32	.4	
West Virginia	1,342,270	15,323.43	15,323.43		.4	787,263.82	762,918.08		19.0	13.5	280,083.23	5.8	283,945.26
Wisconsin	2,431,220	151,529.60	151,529.60		4.7	831,311.48	825,004.65		35.3	18.7	1,184,326.08	24.5	270,359.67
Wyoming	1,125,332	53,504.69	53,004.69		1.0	728,480.25	728,477.07		18.3	15.1	181,882.46	3.2	161,967.78
District of Columbia	959,835	295,510.62	295,510.62		2.4	680,633.97	663,650.15		31.0	2.3			74.23
Hawaii													
TOTALS	114,264,481	6,253,427.70	5,973,180.77	92,036.96	196.4	63,211,391.55	60,924,009.11	395,305.31	24.5	959.5	24,583,867.97	476.9	22,783,423.15

CURRENT STATUS OF U.S. PUBLIC WORKS ROAD CONSTRUCTION AS PROVIDED IN TITLE II, SECTION 204 OF THE NATIONAL INDUSTRIAL RECOVERY ACT

CLASS III—PROJECTS ON SECONDARY OR FEEDER ROADS

AS OF APRIL 30, 1934

STATE	PUBLIC WORKS FUNDS ASSIGNED FOR CLASS III PROJECTS ON SECONDARY HIGHWAYS	COMPLETED			UNDER CONSTRUCTION				APPROVED FOR CONSTRUCTION		BALANCE OF PUBLIC WORKS FUNDS AVAILABLE FOR NEW CLASS III PROJECTS	STATE
		Total cost	Public works funds	Mileage	Estimated total cost	Public works funds allotted	Percentage completed	Mileage	Public works funds allotted	Mileage		
Alabama	$ 2,092,533.00				$ 135,095.17	$ 135,095.17	40.7	5.1	$ 888,321.80	64.5	$ 1,069,116.03	Alabama
Arizona	625,435.00				412,835.88	400,873.89	43.4	32.2	125,602.58	10.1	98,958.53	Arizona
Arkansas	1,687,084.00	$ 11,141.83	$ 11,141.83	0.2	677,384.93	677,384.93	16.8	79.1	355,548.25	57.3	643,008.99	Arkansas
California	3,901,838.00	226,532.81	161,925.10	2.8	2,723,965.67	2,259,569.95	32.0	141.9	641,304.79	23.2	839,038.16	California
Colorado	1,718,632.00	269,262.42	269,262.42	41.7	1,211,910.29	1,176,489.22	50.5	131.2	160,097.64	9.7	112,782.72	Colorado
Connecticut	659,120.00				664,915.58	659,120.00	10.8	14.5				Connecticut
Delaware	454,772.00				161,554.00	161,554.00	15.5	1.8	72,547.50	12.2	220,670.50	Delaware
Florida	1,307,958.00	166,491.36	166,491.36	19.0	1,049,802.53	1,049,802.53	50.6	49.4	38,729.77	.8	52,934.34	Florida
Georgia	2,320,973.00				650,256.71	650,256.71	40.9	42.3	510,335.81	51.1	1,160,380.48	Georgia
Idaho	1,121,562.00	240,026.23	230,797.07	34.3	948,331.25	890,764.93	41.2	111.4				Idaho
Illinois	6,262,223.00	90,725.91	90,725.91	23.1	4,016,285.04	4,016,285.04	17.5	239.3	1,128,576.05	55.4	1,026,636.00	Illinois
Indiana	501,892.00				380,774.32	380,774.32	13.9	52.9	121,117.68	16.2		Indiana
Iowa	2,212,245.00	85,658.05	83,000.00	27.3	1,049,882.42	998,950.00	34.7	127.7	844,700.00	86.2	285,595.00	Iowa
Kansas	2,522,401.00	11,865.47	11,865.47	3.8	2,038,801.25	2,027,934.29	35.2	151.0	467,585.91	9.5	15,015.33	Kansas
Kentucky	1,879,340.00	181,969.52	181,969.52	22.4	1,453,742.94	1,453,742.94	29.6	172.0	202,881.88	21.1	40,745.66	Kentucky
Louisiana	1,457,148.00	61,627.65	61,627.65	2.3	540,834.03	540,834.03	12.0	27.9	593,981.05	16.0	260,705.27	Louisiana
Maine	842,479.00	486,989.39	486,986.99	49.7	420,558.60	340,074.53	91.7	36.5	8,989.70	.2	6,427.78	Maine
Maryland	891,132.00				448,056.92	448,056.92	30.1	34.9	280,626.45	18.3	162,448.63	Maryland
Massachusetts	488,185.00				469,741.41	469,741.41	42.2	15.2			18,443.59	Massachusetts
Michigan	3,184,057.00	88,500.00	88,500.00	7.4	2,387,000.00	2,387,000.00	9.6	185.4	421,950.00	31.8	286,607.00	Michigan
Minnesota	2,131,314.00	45,666.23	45,666.23	34.6	1,557,346.39	1,476,915.39	39.8	223.5	194,428.52	9.2	414,303.86	Minnesota
Mississippi	1,744,669.00				459,999.99	459,999.99	52.8	54.6	337,534.77	37.1	947,134.24	Mississippi
Missouri	2,923,273.00	30,275.23	30,275.23	7.7	2,623,965.44	2,623,965.44	56.6	467.7	250,117.33	20.1	18,915.00	Missouri
Montana	1,859,937.00	250,772.55	250,772.55	33.6	1,295,827.72	1,295,827.72	3.5	160.5	281,627.19	28.7	31,709.54	Montana
Nebraska	1,957,840.00	16,621.93	16,621.93	15.2	1,849,229.15	1,829,980.23	39.5	241.6	110,637.84	27.1		Nebraska
Nevada	1,136,479.00	187,125.76	187,125.76	14.8	792,873.80	792,873.80	49.8	86.2	36,585.76	2.7	119,893.68	Nevada
New Hampshire	477,460.00				518,207.67	477,383.82	47.3	25.6			76.18	New Hampshire
New Jersey	56,550.52				56,550.52	56,550.52	30.1	.5				New Jersey
New Mexico	1,448,234.00	291,500.00	291,500.00	64.7	652,000.00	652,000.00	57.4	247.8	95,499.53	10.9	409,234.47	New Mexico
New York	3,608,768.00	233,621.33	233,621.33	10.8	3,786,800.00	3,355,375.00	19.4	88.7	9,275.00	.1	10,496.67	New York
North Carolina	2,380,573.00	158,831.55	158,631.48	18.4	1,087,336.67	1,087,336.67	54.2	98.9	211,203.47	26.7	923,401.38	North Carolina
North Dakota	1,451,112.00				46,035.01	46,035.01	10.9	10.3	230,270.50	32.5	1,174,806.49	North Dakota
Ohio	3,871,148.00	225,440.00	225,440.00	78.3	3,261,880.00	3,024,904.90	27.6	218.8	416,200.00	7.8	204,603.10	Ohio
Oklahoma	2,304,199.00				590,374.75	590,374.75	16.6	55.0	1,635,542.71	210.4	78,281.54	Oklahoma
Oregon	1,526,724.00				1,129,874.44	1,019,991.42	36.9	60.5	486,658.00	48.0	20,074.58	Oregon
Pennsylvania	7,344,822.00	40,096.00	40,096.00	4.9	6,424,728.04	6,350,125.84	28.5	588.5	734,160.25	63.3	220,439.91	Pennsylvania
Rhode Island	499,677.00				412,010.22	412,010.22	11.4	33.2			87,666.78	Rhode Island
South Carolina	1,364,791.00				1,174,986.08	1,174,986.08	44.0	133.8	110,233.65	12.7	79,571.27	South Carolina
South Dakota	1,502,870.00	66,805.85	66,805.85	32.8	247,149.43	247,149.43	22.2	75.6	140,607.64	54.9	1,048,307.08	South Dakota
Tennessee	2,123,155.00				1,082,018.78	1,082,018.78	34.9	89.1	465,207.98	40.3	575,928.24	Tennessee
Texas	6,061,006.00	752,743.58	565,520.59	134.5	5,142,149.72	4,422,255.78	46.0	601.7	398,089.67	27.6	675,139.96	Texas
Utah	1,048,677.00	382,032.68	365,511.34	69.5	560,641.16	544,391.65	35.6	86.7	93,967.69	8.0	44,806.32	Utah
Vermont	438,880.00				336,541.00	318,237.70	24.2	29.2	120,163.79	7.2	478.51	Vermont
Virginia	1,854,189.00	82,084.91	65,000.72	31.0	1,390,470.60	1,307,685.69	50.3	173.0	369,036.69	4.4	112,465.90	Virginia
Washington	1,180,362.00	131,043.12	131,043.12	16.2	925,200.89	915,200.89	28.2	47.2	27,739.30	3.9	106,378.69	Washington
West Virginia	1,118,559.00	5,979.96	5,979.96		896,461.92	896,461.92	16.1	50.7	141,115.69	9.1	75,001.43	West Virginia
Wisconsin	2,431,220.00	223,248.44	223,248.44	7.8	1,540,061.70	1,465,214.29	12.6	98.2	578,231.84	63.1	164,525.43	Wisconsin
Wyoming	1,125,332.00	388,313.29	377,284.00	48.4	596,172.42	585,978.00	17.3	91.4	102,371.05	10.9	59,698.95	Wyoming
District of Columbia	959,234.00	110,674.64	110,674.64	2.0	848,409.36	848,409.36	26.8	5.7			150.00	District of Columbia
Hawaii	187,106.00				177,717.69	177,717.69	23.1	4.9			9,388.31	Hawaii
TOTALS	94,248,569.52	5,543,667.69	5,235,112.49	859.2	63,304,749.50	60,664,662.79	32.1	5,800.8	14,439,402.72	1,250.3	13,909,391.52	TOTALS

PUBLICATIONS *of the* BUREAU OF PUBLIC ROADS

Any of the following publications may be purchased from the Superintendent of Documents, Government Printing Office, Washington, D.C. As his office is not connected with the Department and as the Department does not sell publications, please send no remittance to the United States Department of Agriculture.

ANNUAL REPORTS

Report of the Chief of the Bureau of Public Roads, 1924. 5 cents.

Report of the Chief of the Bureau of Public Roads, 1927. 5 cents.

Report of the Chief of the Bureau of Public Roads, 1928. 5 cents.

Report of the Chief of the Bureau of Public Roads, 1929. 10 cents.

Report of the Chief of the Bureau of Public Roads, 1931. 10 cents.

Report of the Chief of the Bureau of Public Roads, 1932. 10 cents.

DEPARTMENT BULLETINS

No. 136D . . Highway Bonds. 20 cents.

No. 347D . . Methods for the Determination of the Physical Properties of Road-Building Rock. 10 cents.

No. 532D . . The Expansion and Contraction of Concrete and Concrete Roads. 10 cents.

No. 583D . . Reports on Experimental Convict Road Camp, Fulton County, Ga. 25 cents.

No. 660D . . Highway Cost Keeping. 10 cents.

No. 1279D . . Rural Highway Mileage, Income, and Expenditures, 1921 and 1922. 15 cents.

TECHNICAL BULLETINS

No. 55T . . Highway Bridge Surveys. 20 cents.

No. 265T . . Electrical Equipment on Movable Bridges. 35 cents.

MISCELLANEOUS CIRCULARS

No. 62MC . . Standards Governing Plans, Specifications, Contract Forms, and Estimates for Federal-Aid Highway Projects. 5 cents.

No. 93MC . . Direct Production Costs of Broken Stone. 25 cents.

MISCELLANEOUS PUBLICATION

No. 76MP . . The results of Physical Tests of Road-Building Rock. 25 cents.

No. —— . . Federal Legislation and Regulations Relating to Highway Construction. 10 cents.

REPRINT FROM PUBLIC ROADS

Reports on Subgrade Soil Studies. 40 cents.

Single copies of the following publications may be obtained from the Bureau of Public Roads upon request. They cannot be purchased from the Superintendent of Documents.

SEPARATE REPRINT FROM THE YEARBOOK

No. 1036Y . . Road Work on Farm Outlets Needs Skill and Right Equipment.

TRANSPORTATION SURVEY REPORTS

Report of a Survey of Transportation on the State Highway System of Ohio (1927).

Report of a Survey of Transportation on the State Highways of Vermont (1927).

Report of a Survey of Transportation on the State Highways of New Hampshire (1927).

Report of a Plan of Highway Improvement in the Regional Area of Cleveland, Ohio (1928).

Report of a Survey of Transportation on the State Highways of Pennsylvania (1928).

Report of a Survey of Traffic on the Federal-Aid Highway Systems of Eleven Western States (1930).

A complete list of the publications of the Bureau of Public Roads, classified according to subject and including the more important articles in PUBLIC ROADS, may be obtained upon request addressed to the U.S. Bureau of Public Roads, Willard Building, Washington, D.C.

CURRENT STATUS OF U.S. PUBLIC WORKS ROAD CONSTRUCTION
AS PROVIDED IN TITLE II, SECTION 204 OF THE NATIONAL INDUSTRIAL RECOVERY ACT

SUMMARY OF CLASSES I, II, AND III
AS OF APRIL 30, 1934

STATE	TOTAL APPORTIONMENT OF PUBLIC WORKS FUNDS	COMPLETED				UNDER CONSTRUCTION					APPROVED FOR CONSTRUCTION		BALANCE OF PUBLIC WORKS FUNDS AVAILABLE FOR ALL NEW PROJECTS
		Total cost	Public works funds	Regular Federal aid	Mileage	Estimated total cost	Public works funds allotted	Regular Federal aid allotted	Percentage completed	Mileage	Public works funds allotted	Mileage	
Alabama	$ 8,370,133	$ 227,967.71	$ 168,533.44	$ 59,434.27	6.5	$ 5,803,125.45	$ 3,499,051.48	$ 2,304,073.97	42.7	308.6	$ 1,922,884.82	109.5	$ 2,779,663.26
Arizona	5,211,960	1,200,957.35	1,200,957.35		80.3	3,395,638.57	2,823,299.76		35.6	230.0	703,815.71	20.2	483,887.18
Arkansas	6,748,335	147,599.21	111,254.21	36,345.00	6.5	3,894,972.83	3,374,252.18	520,720.65	37.5	214.0	1,646,755.47	120.4	1,616,073.14
California	15,607,354	2,454,602.68	2,087,338.64		72.0	12,783,432.84	10,122,166.81		31.8	384.0	2,296,211.38	63.4	1,141,637.17
Colorado	6,874,530	1,593,092.76	1,547,285.11		123.5	4,140,807.12	4,094,805.70		38.2	209.4	844,850.83	27.4	387,578.36
Connecticut	2,865,740	48,325.68	48,325.68		.5	2,882,272.43	2,699,870.82	175,778.94	16.1	54.4	104,493.49	.6	13,050.01
Delaware	1,819,088	208,841.80	208,841.80		.8	1,118,269.20	1,118,269.20		25.9	21.1	153,652.50	13.2	338,324.50
Florida	5,231,834	817,672.00	607,854.94	209,817.06	38.6	5,060,215.28	4,246,382.92	813,222.26	46.2	156.0	168,875.92	8.0	208,720.22
Georgia	10,091,185	636,616.43	636,616.43		31.6	3,872,658.70	3,872,658.70		44.8	229.8	1,869,292.28	123.5	3,712,617.59
Idaho	4,486,249	729,740.99	716,718.57		88.5	2,813,657.71	2,738,621.08		41.1	228.0	497,396.71	18.4	533,312.64
Illinois	17,570,770	149,508.29	149,508.29		23.9	11,419,397.15	11,419,397.15		17.7	336.8	3,857,092.56	84.5	2,144,772.00
Indiana	10,037,843	42,730.27	42,730.27		.8	3,042,297.51	3,042,297.51		26.9	137.5	4,965,002.43	117.5	1,987,812.79
Iowa	10,055,660	1,052,926.38	1,046,850.00		67.5	6,565,826.02	6,193,375.00		36.8	379.2	1,563,300.00	110.1	1,252,135.00
Kansas	10,089,604	839,760.23	839,760.23		140.4	8,712,846.87	8,385,294.13		47.0	441.1	847,977.56	17.3	16,572.08
Kentucky	7,517,359	344,145.14	340,275.01		34.7	4,681,896.99	4,681,896.99		29.2	385.6	1,123,727.68	62.9	1,371,459.32
Louisiana	5,828,591	282,260.87	282,260.87		6.7	3,495,982.90	2,989,331.90		29.3	103.3	2,094,688.82	41.6	462,309.41
Maine	3,369,917	565,418.66	565,292.70		51.3	2,003,967.88	1,887,916.86		49.5	81.9	734,627.24	14.2	182,080.20
Maryland	3,564,527					1,265,989.46	1,252,190.71		21.6	50.3	597,498.20	24.7	1,714,838.09
Massachusetts	6,597,100	207,833.37	114,849.13	92,984.24	5.7	5,651,438.97	5,321,679.33	329,759.64	83.8	61.5	262,815.16	1.0	897,756.38
Michigan	12,736,227	332,200.00	332,200.00		11.4	8,306,316.00	8,304,166.00		17.7	392.5	2,561,366.00	100.9	1,538,495.00
Minnesota	10,656,569	2,334,649.35	2,334,649.35		454.6	4,499,504.86	4,419,073.86		35.5	513.8	1,582,234.24	122.6	2,320,611.55
Mississippi	6,978,675	258,580.03	184,956.66	73,623.37	9.5	4,583,967.16	2,854,225.59	1,691,109.63	31.9	270.8	1,230,873.16	93.5	2,708,619.59
Missouri	12,180,306	631,726.86	504,793.33		38.6	8,653,491.59	8,148,642.25	90,048.60	49.9	646.7	1,283,677.77	44.7	2,243,192.65
Montana	7,439,748	1,044,007.01	1,044,007.01		112.5	5,628,358.98	5,215,557.55	332,801.43	85.7	432.3	939,812.52	64.7	240,370.92
Nebraska	7,828,961	422,743.37	300,134.58		163.6	7,680,284.35	6,562,867.36	108,538.00	40.9	466.3	965,503.82	49.1	455.84
Nevada	4,545,917	791,112.80	791,112.80		98.5	2,917,451.74	2,917,451.74		36.4	257.7	629,103.68	15.8	208,248.78
New Hampshire	1,909,839					1,695,372.50	1,648,041.24		35.5	49.8	182,283.78	3.1	79,513.98
New Jersey	6,346,039	112,495.14	112,495.14		2.3	5,387,247.49	5,178,193.48	169,466.42	18.7	53.7	139,354.99	.5	915,995.39
New Mexico	5,792,935	1,794,996.55	1,794,996.55		235.5	3,326,284.14	3,189,924.66	102,921.33	87.2	379.8	222,095.20	16.8	585,918.59
New York	22,330,101	672,903.01	572,521.71	43,000.00	20.3	21,860,666.88	19,816,083.68	354,000.00	22.4	367.1	1,180,014.85	13.9	761,480.76
North Carolina	9,522,293	963,094.10	705,116.28	257,777.75	79.2	4,416,382.69	4,097,496.29	316,790.92	44.1	496.2	1,829,135.37	207.2	2,890,545.06
North Dakota	5,804,448	512,910.67	512,907.16		266.8	1,609,859.86	1,530,678.28	79,181.58	18.6	390.3	1,634,979.40	336.0	2,125,683.16
Ohio	15,484,592	714,759.21	701,472.65		90.0	13,761,067.43	12,854,544.33	51,410.00	29.1	434.3	1,583,784.00	30.2	344,791.02
Oklahoma	9,216,798	342,005.89	341,880.28		24.4	5,804,701.56	5,804,701.56		36.8	329.8	2,383,876.10	252.6	686,340.06
Oregon	6,106,896	730,153.83	617,942.83		52.2	4,678,489.06	4,391,903.25	72,821.40	33.3	207.0	753,170.52	57.7	343,879.40
Pennsylvania	18,891,004	234,493.72	233,661.88		10.2	13,943,189.44	13,781,831.81		23.9	736.8	3,165,694.14	95.7	1,709,816.17
Rhode Island	1,998,708	18,144.13	18,144.13		.5	1,742,721.82	1,742,721.82		23.4	58.5	66,224.98	1.1	171,617.07
South Carolina	5,459,165	88,849.90	88,849.90		2.9	3,564,971.70	3,561,837.07	3,134.63	43.8	339.1	780,038.02	59.2	1,028,440.01
South Dakota	6,011,479	918,039.65	898,698.26	19,341.39	160.1	1,990,833.43	1,900,695.01	90,138.22	25.1	325.4	1,399,925.03	163.1	1,812,160.70
Tennessee	8,492,619	424,772.73	339,300.12	85,472.61	14.0	5,613,853.46	5,123,308.69	490,544.77	36.2	237.7	1,440,634.87	84.5	1,589,375.32
Texas	24,244,024	2,781,003.64	2,153,625.78		478.5	17,135,300.91	15,378,082.30		38.3	1,272.4	2,921,114.22	145.5	3,791,201.70
Utah	4,194,708	1,757,703.33	1,728,359.86		188.7	1,948,680.72	1,902,761.74		38.8	175.7	223,916.21	11.3	339,670.19
Vermont	1,867,573	51,837.88	51,837.88		6.9	1,457,044.03	1,401,099.78		29.9	74.1	399,792.48	14.9	14,842.86
Virginia	7,416,757	679,039.43	634,730.38	27,224.86	54.0	5,307,956.22	4,917,438.87	110,659.96	32.6	262.3	1,658,759.07	65.9	205,828.68
Washington	6,115,867	752,478.98	740,397.76		39.8	4,828,086.65	4,812,025.10	3,356.82	33.2	150.9	453,858.89	15.7	109,585.25
West Virginia	4,474,234	216,185.21	216,185.21		6.8	3,296,778.46	3,266,432.72		29.6	127.9	552,999.60	17.1	438,656.47
Wisconsin	9,724,881	682,291.18	671,988.35	1,190.00	28.2	5,142,225.72	4,992,255.71	21,500.00	29.7	225.9	3,225,801.96	185.3	834,834.98
Wyoming	4,501,327	1,354,543.88	1,227,419.69	78,000.00	213.2	2,757,550.82	2,630,995.07	58,200.00	18.4	386.5	391,961.53	28.8	250,950.71
District of Columbia	1,918,469	406,185.26	406,185.26		4.4	1,529,043.33	1,512,059.51		28.6	8.0			224.23
Hawaii	1,871,062	85,729.28	72,722.15	12,994.32	4.2	1,556,817.15	1,321,537.00	185,260.15	22.8	30.2	218,780.78	3.3	258,082.07
TOTALS	394,000,000	33,659,635.84	31,048,545.61	997,204.87	3,651.6	269,229,133.43	248,941,591.55	8,435,459.32	31.6	14,111.4	62,215,635.94	3,279.1	51,794,226.90